

SECOND EDITION

THE  
**Exoplanet**  
HANDBOOK

Michael Perryman

CAMBRIDGE





# **The Exoplanet Handbook**

Second Edition

With the discovery of planets beyond our solar system 25 years ago, exoplanet research has expanded dramatically, with new state-of-the-art ground-based and space-based missions dedicated to their discovery and characterisation. With more than 3500 exoplanets now known, the complexity of the discovery techniques, observations, and physical characterisation has grown substantially. This handbook ties all these avenues of research together across a broad range of exoplanet science. Planet formation, exoplanet interiors and atmospheres, and habitability are discussed, providing in-depth coverage of our knowledge to date. Comprehensively updated from the first edition, this book includes instrumental and observational developments, in-depth treatment of the new Kepler mission results and hot Jupiter atmospheric studies, and major updates on models of exoplanet formation. With extensive references to the research literature and appendices covering all individual exoplanet discoveries, it is a valuable reference to this exciting field for both incoming and established researchers.

During a 30-year career with the European Space Agency (ESA), Michael Perryman was the scientific leader of the Hipparcos astrometry mission, 1981–97, also serving as project manager for its operational phase, 1989–93. With Lennart Lindegren, he was the co-originator of the Gaia astrometry mission, a project expected to make important contributions to exoplanet science in the coming years. He was ESA's project scientist for Gaia from its earliest concepts in 1995 until the Critical Design Review in 2008, establishing the payload concept, technical feasibility, operational and data analysis principles, and its organisational structure, and coordinating its scientific case. He was Professor of Astronomy at Leiden University between 1993 and 2009, and Bohdan Paczyński Visiting Professor at Princeton University in 2013.

## Praise for the First Edition

'*The Exoplanet Handbook* by Michael Perryman is an exhaustive reference for the techniques, facts and theory of exoplanet science. An excellent and objective resource for novice and expert alike, this compendium is destined for the libraries of all serious students of the art.' Adam Burrows, Princeton University

'Perryman's book is truly a major achievement: it is an astonishingly complete overview of everything we know about exoplanets. *The Exoplanet Handbook* will serve as the seminal reference in this field for many years. I would (and will) strongly encourage any graduate students interested in doing serious research in exoplanets to buy a copy of this book.' B. Scott Gaudi, The Ohio State University

'Michael Perryman's new book provides not only a thorough discussion of what we have learnt about extrasolar planets since the first discoveries over 15 years ago, but also a clear and comprehensive review of the wide range of observational and theoretical techniques that have been employed to find and characterise them. This volume is a must-have for serious researchers in the field, and will be an invaluable reference for many years to come.' I. Neill Reid, Space Telescope Science Institute

'... more technically detailed and comprehensive than many of the rival texts. ... it is an ideal companion for a Ph.D. student in the field, as well as an excellent reference for the experienced researcher ... this is also an excellent, detailed textbook suitable for a specialist undergraduate or postgraduate lecture course.' *The Observatory*

'If I were allowed access to only one book on the subject of extra-solar planets, Michael Perryman's *The Exoplanet Handbook* is a contender that would be very hard to beat. The book documents the whirlwind development of this newly-emergent and energetic new field of science ... It is also a compendium of essential physical concepts, useful formulae and computational strategies for analysis of the various types of astronomical data used to discover and characterise exoplanets.' Andrew Collier Cameron, University of St Andrews

'This remarkable compilation brings together observations and theoretical explorations of a rapidly growing astronomical field. Literally every possible observational method is explained and recent results given ... While the number of known exoplanets changes weekly, the methods through which we discover and characterise these do not. Highly recommended.' George F. Benedict, University of Texas, Austin

'*The Exoplanet Handbook* provides a very valuable integration of all aspects of the fascinating and interdisciplinary world of exoplanet science. It combines in a coherent context the presentation of the observational techniques, covering recent highlights and future prospects, with the description of the vast range of intertwining phenomena and processes that shape the paths of planet formation, evolution and structure ... *The Handbook* is an invaluable resource for professional planetary scientists and academic teachers, for both practising astronomers and motivated amateurs, and for advanced undergraduate and graduate students.' Vittorio Vanzani, Padua University

'This *Handbook* is a true encyclopedic reference on exoplanets. Perryman's new book is a comprehensive review on major programs and results obtained in the last decade in this exciting new domain of astrophysics and as such it is a priceless resource for experts. The detailed descriptions of the foundations of the main observations techniques and key theoretical aspects make it a perfect book for any student wishing to have a comprehensive introduction to exoplanet research. This volume is likely to become an important reference in the field.' Didier Queloz, Geneva Observatory

'*The Exoplanet Handbook* by Michael Perryman is impressive; the content is of high level and very accurate. He has succeeded in providing an exhaustive and up-to-date review of this mature and rich field. *The Handbook* will surely help Ph.D. students and professional astronomers who want to learn about this field. It will even be useful to experts who want to check details on some specific aspects, either about exoplanets themselves, detection methods, or instrumentation.' Jean Schneider, CNRS/LUTH, Paris Observatory

'... Michael Perryman ... has written an excellent, startlingly complete snapshot of the current state of knowledge regarding extrasolar planets ... Like any good encyclopedia, *The Exoplanet Handbook* has as its major strength its reference list, which cites more than 4000 papers. The list provides a near-complete snapshot of all the research that has taken place in the field in the past two decades. Furthermore, the references are deftly integrated into the text, which makes this volume an excellent point of departure for any researcher seeking to chart a new course of exoplanetary investigation.' Gregory Laughlin, *Physics Today*

# The Exoplanet Handbook

Second Edition

Michael Perryman

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# Preface to the Second Edition

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Almost 20 years ago, with the subject still in its infancy, and the number of known exoplanets at just 34, I prepared a 60-page review of exoplanet research (Perryman, 2000). The first edition of the *Exoplanet Handbook*, published in early 2011, grew out of this: a book-length review to the end of 2010, when the number of known planets was just over 500. The aim of both was to collect in one place a synthesis of the knowledge of the many areas of exoplanet research.

Since then progress has continued to flourish. The number of known exoplanets now exceeds 3500, and the research literature stands at more than 17 000 refereed papers. My goal in this second edition remains the same: to collect in one place, and in unified form, an overall perspective of the many areas of ongoing research, and to provide a synthesis of the developments, discoveries, and associated physical phenomena, with pointers to the more detailed literature. It offers a framework for understanding the wider and more definitive research literature, through to the end of 2017.

Amongst many revisions, and a few minor suppressions, there are extensive additions: I have included the numerous advances in radial velocity, microlensing, imaging (notably SPHERE, GPI, and ALMA), and transit instruments. The latter includes the important and growing class of bright star transiting systems from HATNet, SuperWASP, and others, as well as the transformational results from the Kepler mission. I have also added more on progress in quantifying habitability and the search for life, and associated considerations such as the anthropic principle, SETI and the Fermi paradox, and many related aspects of solar system research.

Much progress has also been made on the theoretical side. Amongst these are advances in the understanding of possible formation pathways via the hypothesised mechanism of pebble accretion; of the formation and dynamical state of multi-planet systems especially in connection with resonance capture; of numerous applications of tidal theory; of the widespread application of atmospheric general circulation models (originally developed for understanding the climate of the Earth and the other solar system planets); and of the development of migration models for the early solar system with their considerable explanatory and predictive content.

Publication of this second edition coincides with a minor respite in the flow of transformational observations which marked the Kepler results, and the start of the second-generation imaging programmes. Significant new insights will be seen again in 2018–20 with the observational advances that will come with the second data release from Gaia (DR2), and the launches of the Transiting Exoplanet Survey Satellite (TESS), CHEOPS, and the James Webb Space Telescope (JWST).

To emphasise the self-evident, this is primarily a review of the status of the field. In places, I have used authoritative text more-or-less directly from the works referenced, implicitly credited to the source. In a work of such extent, I inevitably cover many topics in which I have no specific expertise. My hope is that the benefits of a broad, up-to-date, uniform treatment, outweigh any imperfections and errors that will exist as a result.

A specific challenge faced in this compilation is the organisation of material, which is now so deeply interconnected, and which contributes to its fascination. I made an early decision to maintain the chapter organisation used for the first edition: it probably remains as logical as any, despite the material related to transits now being substantially more extensive than any others. Bibliographic appendixes collect detailed results for each system, and are intended to permit a rapid overview of which systems have been found, assess their scientific interest to date, allow the chronology of understanding for each to be traced, and permit a direct (hyperlinked) access to the relevant ADS and NASA Exoplanet Archive entries.

The partitioning of topics is, as in any library cataloguing system, non-trivial. As just one of countless examples, while it might well be convenient to find all material on ‘hot Jupiters’ in one section, this obviously cannot be done without the consequences of dividing up material on obliquities, Lidov–Kozai migration, formation, spectroscopy, and so on.

Another challenge was how to handle the references, and what to include. While the subject is developing so rapidly, I considered that the source of material cited should be retained, in part for verification, in part to give due credit, but more crucially as the entry points for further research. Considering and dismissing various alter-

natives (such as retaining only the most frequently-cited references, omitting titles, or only making them available online), does result in an extensive bibliography. It has the same reference/text ratio as the first edition, with its merits and with its disadvantages.

I have attempted to make the references to, and statistics of, exoplanet discoveries, and the associated literature, as complete as feasible through to the end of 2017. The fact that some publications were only in preprint form at that time, combined with a limited attempt to track some new studies after that cutoff, leads to some publications dated 2018.

Amongst the uncountable gaps in current knowledge, a few are perhaps notable. From the observational side, no definitive exomoons, planetary rings, or co-orbiting planets have yet been found. The detailed form of the exoplanet distribution function remains poorly known. There is no evidence for life, in any form, beyond Earth.

From the theoretical side, many details of planet formation remain uncertain, as does the fraction of gas giants formed by core accretion or gravitational instability. There is no widely embraced paradigm for the formation, halting, or inflated radii of hot Jupiters, for the formation of super-Earths, or for the Kepler ‘dichotomy’.

Within the solar system, open questions include the source of the transient heating of the early solar nebula, the origin of the solar obliquity, the size (or even presence) of Jupiter’s solid core, and to what extent gas and planetesimal migration have influenced its present architecture. More definitive answers to some of these questions may, perhaps, accompany the third edition.

I owe a number of people my sincere thanks for their assistance. I am pleased to thank the Directors of the Kiepenheuer Institute for Solar Physics (Freiburg), Oskar von der Lühe and Svetlana Berdyugina, for a period as visiting fellow in 2016, when the major parts of Chapters 6–7 were completed.

I am grateful to the Director of the Instituto de Astrofísica de Andalucía (IAA), José Vilchez, and to Pedro Amado González, for a visit to Granada in early 2017, when Chapters 10–12 were largely completed.

I thank Dr Joan Megson and John Gray for the use of their retreat in Assynt, which allowed me to complete some other sections, and to compile the appendixes, with the minimum of distraction.

As for the first edition, I express my particular gratitude to Joachim Wambsganss, director of the Zentrum für Astronomie der Universität Heidelberg (ZAH/ARI), and to Thomas Henning and Hans-Walter Rix, directors of the Max-Planck-Institut für Astronomie, Heidelberg, for their invitation to spend a period in Heidelberg to prepare the first edition in 2010, and for very kindly hosting a further period in Heidelberg in early 2018 to finalise this second edition.

Various people have kindly responded to my specific questions, and here I am grateful to Adam Burrows, Ludmila Carone, Andrew Collier Cameron, Jeff Coughlin, Jos de Bruijne, Laurance Doyle, Dainis Dravins, Jonathan Fortney, Joel Hartman, René Heller, Brian Jackson, Anders Johansen, Hubert Klahr, Heather Knutson, Lennart Lindegren, Abel Méndez, Jerry Orosz, Joshua Pepper, Don Pollacco, Saul Rappaport, Tom Ruen, Birger Schmitz, Alberto Sesana, John Southworth, Jason Wang, and Peter Wheatley.

Again, I am most grateful to all authors who agreed to the use of their figures for this work, which are so invaluable for illustrating the various results. Their names are acknowledged in the figure captions.

I am grateful to Simon Mitton, who encouraged the publication of the first edition, and to Lorraine Hanlon for the valuable support of University College Dublin.

I also thank Neil Thomas (University of Florida), and Vittorio Vanzani (University of Padua) who communicated errors in the first edition.

The NASA Astrophysics Data System (ADS), combined with on-line journal access, has been indispensable for a literature survey on this scale. L<sup>A</sup>T<sub>E</sub>X, TeXShop, and BibDesk were key to its practical development. Various online resources, notably the NASA Exoplanet Archive and the Extrasolar Planets Encyclopaedia, have been invaluable.

As for the first edition, I thank Vince Higgs and colleagues at Cambridge University Press, including for this edition Esther Miguélez Obanos, for their highly constructive and efficient support.

Finally, I owe a considerable debt of gratitude to my wife Julia. Her support, enthusiasm and indeed her interest has been of immense help.

The electronic pdf version includes hyperlinked navigation via the Table of Contents, via the Index, as well as through cross-referenced sections, figures, and equations. References and Appendixes are hyperlinked as below, with the References including links both to the relevant ADS pages, and back-referencing to the cited pages.

A number of files are made available at the location [www.cambridge.org/exoplanethandbook](http://www.cambridge.org/exoplanethandbook). A pdf version of the References includes hyperlinks to the relevant ADS pages. Appendixes with planet listings (Appendixes C–F) are hyperlinked at the host star level to the NASA Exoplanet Archive, with each citation also hyperlinked to the relevant ADS page. Some figures are also made available at the same location.

Notification of errors, major or minor, or significant omissions or misrepresentations, will be greatly appreciated ([mac.perryman@gmail.com](mailto:mac.perryman@gmail.com)), and will be maintained at the same [www](http://www) location.

Michael Perryman  
Heidelberg, April 2018

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# Introduction

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## 1.1 The challenge

THERE ARE HUNDREDS OF BILLIONS of galaxies in the observable Universe, with each galaxy such as our own containing some hundred billion stars. Surrounded by this seemingly limitless ocean of stars, mankind has long speculated about the existence of planetary systems other than our own, and the possibility of life existing elsewhere in the Universe.

Only recently has evidence become available to begin to distinguish the extremes of thinking that has pervaded for more than 2000 years, with opinions ranging from ‘*There are infinite worlds both like and unlike this world of ours*’ (Epicurus, 341–270 BCE) to ‘*There cannot be more worlds than one*’ (Aristotle, 384–322 BCE).

Shining by reflected starlight, exoplanets comparable to solar system planets will be billions of times fainter than their host stars and, depending on their distance, at angular separations from their accompanying star of, at most, a few seconds of arc. This combination makes direct detection extraordinarily demanding, particularly at optical wavelengths where the star/planet intensity ratio is large, and especially from the ground given the perturbing effect of the Earth’s atmosphere.

Alternative detection methods, based on dynamical perturbation of the star by the orbiting planet, delivered the first tangible results around 1990. Radio pulsar timing achieved the first convincing detection of planetary mass bodies beyond the solar system (Wolszczan & Frail, 1992). High-accuracy radial velocity (Doppler) measurements yielded the first suggestions of planetary-mass objects surrounding main sequence stars from the late 1980s (Campbell et al., 1988; Latham et al., 1989; Hatzes & Cochran, 1993), with the first essentially unambiguous detection in 1995 (Mayor & Queloz, 1995).

**Progress since 1995** This discovery precipitated a changing mindset. The search for exoplanets, and their characterisation, rapidly became a respectable domain for scientific research, and one equally quickly supported by funding authorities. More planets were discovered by radial velocity search teams in the following years. In 1998, the technique of gravitational micro-

lensing provided evidence for a low-mass planet orbiting a star near the centre of the Galaxy nearly 30 000 light-years away, with the first confirmed microlensing planet reported in 2004. In the photometric search for transiting exoplanets, the first transit of a previously-detected exoplanet was reported in 1999, the first *discovery* by transit photometry in 2003, the first of the wide-field bright star survey discoveries in 2004, and the first discovery from space observations in 2008.

While these manifestations of the existence of exoplanets are also extremely subtle, advances in Doppler measurements, photometry, microlensing, timing, imaging, and astrometry, have since provided the tools for their detection in relatively large numbers. Now, almost 25 years after the first observational confirmation, exoplanet detection and characterisation, and advances in the theoretical understanding of their formation and evolution, are moving rapidly on many fronts.

## 1.2 Discovery status

As of the end of 2017, more than 3500 confirmed planets were known, with some 600 multiple systems. Some statistics, according to discovery method, are listed in Table 1.1. An observational chronology, of necessity both selective and subjective, is given in Table 1.2.

**Diversity** Continuing the trend established by the earliest discoveries, exoplanets do not adhere to the individual or system properties extrapolated from the known architecture of the solar system.

Orbital properties vary widely. Many have very elliptical orbits,  $e \gtrsim 0.3$ , compared to the largest eccentricities in the solar system of  $\sim 0.2$  for Mercury and Pluto (and 0.05 for Jupiter). Of planets with estimated masses, some half are around that of Jupiter ( $0.3 - 3M_J$ ), and a number of these orbit their host star much closer than Mercury orbits the Sun (0.39 au): hot highly-irradiated giants piled up towards 0.03 au that are unlikely to have formed *in situ*. Others are located far out, at distances of 100 au or more from their host star. Orbits highly inclined to the star’s equatorial plane occur reasonably frequently, some even with retrograde orbits.

Table 1.1: Exoplanet discovery statistics, from the NASA Exoplanet Archive, 2017 December 31. The table has some simplifications. For example, systems can be multiple with one or more planets discovered through transit measurements, and others in the system discovered by radial velocity follow-up. Some planets designated in the NASA Exoplanet Archive as detected by ‘timing’ were the result of transit timing measurements.

Category	Chapter	Systems	Multiple	Planets
Detections				
Radial velocity	2	504	102	662
Astrometry	3	1	0	1
Timing	4	20	5	32
Microlensing	5	51	2	53
Transits	6	2053	474	2789
Imaging	7	40	2	44
Total				3572

Exoplanets are being discovered around a wide variety of stellar types. Host stars are not only main sequence stars like the Sun, but they include very low-mass stars, low metallicity stars, giant stars, and other advanced evolutionary stages such as white dwarfs and pulsars. Their internal structure and composition vary widely too. Gas giants with stripped outer envelopes, water worlds formed beyond the snow line, and carbon-dominated terrestrial planets may all exist. Exoplanet atmospheres are being probed through transit and secondary eclipse photometry and spectroscopy.

In multi-planet systems, many planets orbit in, or close to, mean motion resonance, presenting a certain challenge to explain their occurrence. Triple-planet Laplace resonances and complex resonance chains have been discovered, as have prominent transit timing variations in multi-planet transiting systems. Systems with low-mass planets are being found in increasing numbers as the radial velocity surveys improve their detection threshold and increase their temporal baseline. High-order multiple systems are being found both from radial velocity and transit surveys, with one known 8-planet transiting system (Kepler-90), one 7-planet transiting system (TRAPPIST-1), and six 6-planet (radial velocity and transiting) systems.

**Frequency** Based on present knowledge from the radial velocity surveys, at least 5–10% of solar-type stars in the solar neighbourhood harbour massive planets. A much higher fraction, perhaps 30% or more, may have planets of lower mass or with larger orbital radii. If these numbers can be extrapolated, the planets in our Galaxy alone would number many billions.

### 1.3 Outline of the treatment

The present volume summarises the main areas of exoplanet research, combining a description of techniques, concepts, and underlying physics, with a review of the associated literature through to the end of 2017.

It is formulated as an overview of all aspects of exoplanet research, intended to be accessible to both astronomers and planetary scientists, emphasising the interconnection between the various fields of investigation, and providing extensive pointers to more in-depth treatments and reviews.

#### 1.3.1 Observational techniques

Chapters 2–7 divide the search for and characterisation of exoplanets according to detection technique. In each case, the underlying principles are summarised, along with the principal instruments in use, the status of experimental results, and the instrumentation planned for the future. Figure 1.1 summarises the various detection techniques that are the subject of these chapters. Figures 1.2–1.3 show the discoveries with time in the form of the development as a function of semi-major axis, and as simple histograms, respectively.

**Radial velocity** Chapter 2 covers the many aspects of radial velocity (Doppler) measurements, including the instrumental approaches being used and under development. It starts with a treatment of planetary orbits, indicating how radial velocity measurements (as well as astrometry, independently and together) provide access to the planet’s orbital parameters. The text covers the basics of wavelength calibration, the contributory error sources, and an overview of the latest results from Doppler searches, including those around binary and multiple stars. The development of sub- $1\text{ m s}^{-1}$ -class accuracies is resulting in the detection of low-mass planets down to just a few Earth masses, which are beginning to appear in large numbers, in multiple systems, and at separations corresponding to the ‘habitable zone’.

**Astrometry** Chapter 3 covers the principles of the detection and characterisation of planetary orbits by astrometric measurement. The limiting factors for ground-based and space-based instruments are summarised. Since the largest astrometric displacements expected for the most massive nearby planets amount to of order 1 milliarcsec, below that detectable from ground, and comparable to the state-of-the-art from space with Hipparcos and HST-FGS, few planets can yet be confirmed through their astrometric displacements, and only one claimed discovery has been by astrometry alone. The panorama of astrometric discovery and characterisation is changing substantially, as this volume goes to press, with the advent of microarcsec accuracies from the space astrometry mission Gaia.

**Timing** Chapter 4 covers exoplanet detection by the measurement of orbit timing residuals, the third discovery technique which makes use of the reflex dynamical motion of the host star. The first non-solar system objects of planetary mass were detected by this technique

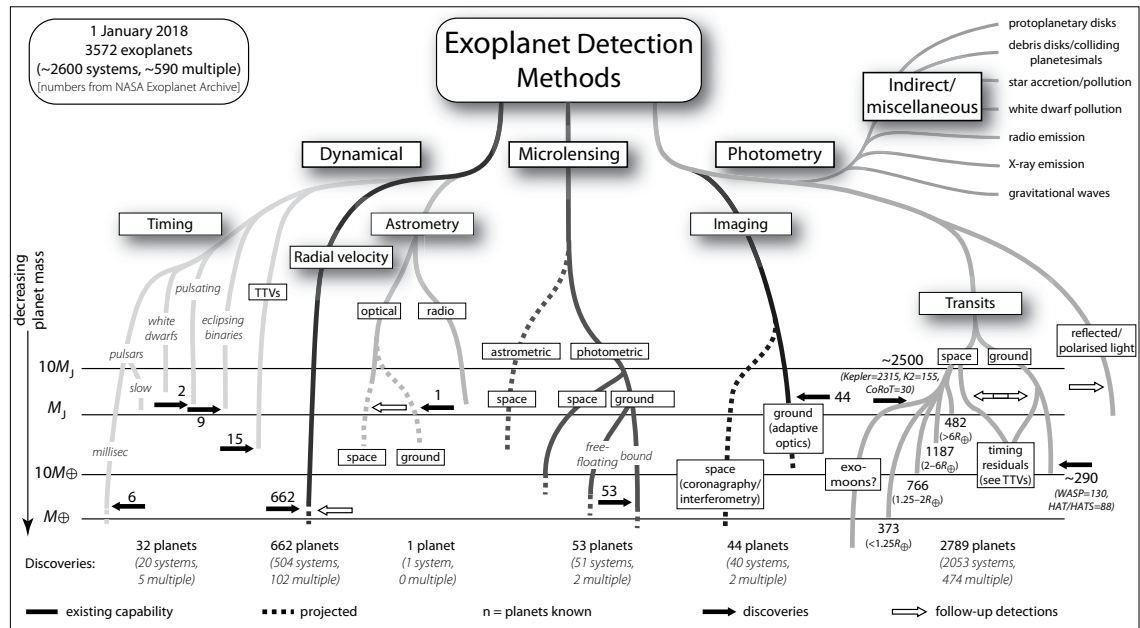


Figure 1.1: Exoplanet detection methods. The lower limits of the lines indicate masses within reach of present measurements (solid lines), and those that might be expected within the next few years (dashed). The (logarithmic) mass scale is shown at left. Miscellaneous signatures to the upper right are less well quantified in mass terms. Solid arrows show relevant discoveries. Open arrows indicate measurements of previously-detected systems. Numbers are from the NASA Exoplanet Archive, 2018 January 1.

using radio pulsar timing in 1991–92. Although pulsars with planets remain the exception, the same technique is being applied to stars which have an underlying periodic photometric signature which is then modulated by an orbiting planet. The technique has been applied to detect planets around pulsating white dwarfs, pulsating subdwarfs, and eclipsing binaries. Its success has underlined the diversity of stellar types around which planets remain in orbit.

**Microlensing** Chapter 5 covers detection by gravitational microlensing. While sampling primarily rather distant systems, its main disadvantage is that it can only provide a single measurement epoch spanning hours or days. A noteworthy milestone was the measurement, reported in 2008, of a 2-planet system in which orbital motion could be measured during the 10-day event duration. The ability to detect true free-floating planets, a sensitivity to Earth-mass planets in the habitable zone and beyond, and a technique independent of the host star spectral type or luminosity class, make the prospects of a space-based microlensing survey of particular importance to a broad exoplanet survey census.

**Photometry and transits** Chapter 6 covers photometric measurements, most importantly the search for exoplanets transiting the disk of their host star, as well as searches for reflected and polarised light. Whilst transits only occur for planets whose orbits happen to lie

essentially orthogonal to the plane of the sky, this constrained geometry allows both the radius of the planet to be determined (at least in terms of the stellar radius), of major importance for exoplanet characterisation, and (under certain assumptions) its mass. Together yielding the exoplanet density, this offers the first insights into the internal structure and chemical composition of the transiting planet. The search for transit time and transit duration variations offers prospects for detecting accompanying members of the planetary system. Important insights into planet atmospheres are being obtained from transit and secondary eclipse spectroscopy.

Transit techniques, and discoveries, have been revolutionised by the Kepler mission, launched in 2009. It has discovered more than 2000 confirmed planets, and searched for other (potentially) transiting bodies, including comets, rings, exomoons, and tidally-disrupted planets. It has identified a wide range of physical effects such as spin-orbit misalignments, apsidal and nodal precession, and planet-planet eclipses, with insights into statistical properties such as co-planarity, multiplicity, resonances, and dynamical packing.

**Direct imaging** Chapter 7 covers the techniques in use and under development for the direct imaging of an exoplanet in orbit around its host star. The technical challenges, and technological solutions (adaptive optics, coronagraphy, and space-based imaging and interfer-

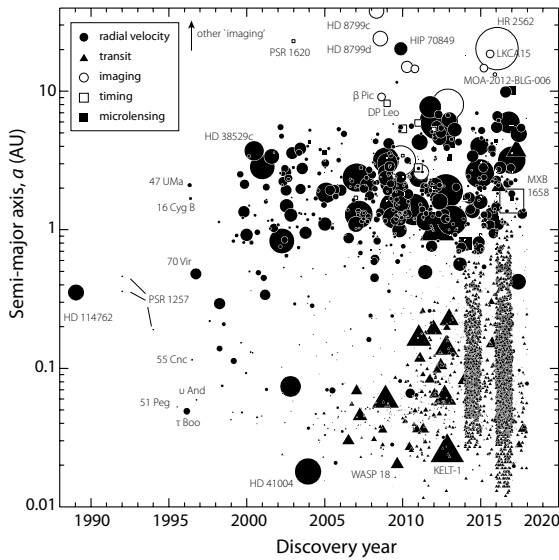


Figure 1.2: Exoplanet discoveries versus year, with content from the NASA Exoplanet Archive as of 2017 December 31. Symbols indicate the discovery method (timing and pulsar planets are taken together, and all Kepler discoveries are taken as ‘transit’ discoveries). If semi-major axes,  $a$ , were not listed, they were estimated from  $P$  and  $M_*$  (Equation 2.17). Symbol sizes are proportional to  $M_p$ , with the largest  $\sim 20\text{--}30M_J$  and the smallest to  $0.2M_J$  or less. Kepler planets without  $M_p$  are shown with small symbols. Scatter within any given discovery year is randomised. The two prominent vertical (Kepler) bands reflect the announcement dates. A few planets are labeled. HD 114762 is a later confirmation of the earlier tentative discovery.

ometry) are described, along with the results obtained to date, including with advanced newly-commissioned second-generation imaging instruments. This chapter also covers prospects for direct detection based on magnetospheric radio emission, as well as observations at mm/sub-mm wavelength.

### 1.3.2 Host star properties and brown dwarfs

**Host stars** Chapter 8 reviews the properties of exoplanet host stars. It includes discussion of their Galactic orbits, their axial rotation, their elemental abundances, and the theories put forward to explain the observed correlation between the occurrence of exoplanets and host-star metallicity. It reviews asteroseismology investigations that have been carried out on a number of host stars, the range of star–planet interactions including characteristics of their X-ray emission, and the inferences being made from white dwarf photospheres.

**Brown dwarfs** Chapter 9 provides an overview of the properties of brown dwarfs. The subject overlaps with that of exoplanets both in the definition of a planet, and in the context of so-called free-floating objects of planetary mass which have been discovered in nearby young star-forming regions.

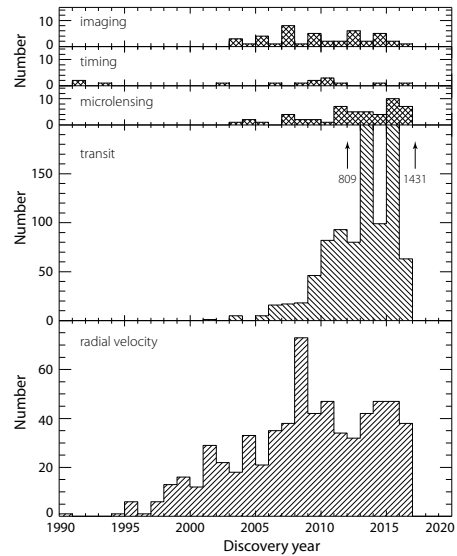


Figure 1.3: Exoplanet discoveries versus year, and detection method, with content from the NASA Exoplanet Archive as of 2017 December 31. The large numbers of Kepler transiting planets announced in 2014 and 2016 are off scale.

### 1.3.3 Theoretical considerations

Chapters 10–11 deal with the theories of formation and evolution, and of their interiors and atmospheres.

**Formation and evolution** Chapter 10 is a summary of the present understanding of planet formation and evolution. Very broadly, the current picture is that formation started with a collapsing protostellar disk, with planets assembled from dust and gas by the progressive agglomeration of material over some 14 orders of magnitude in size. The gas and ice giants, of masses  $\geq 10M_{\oplus}$ , formed by either, perhaps both, core accretion or gravitational disk instability. Close-in planets, high eccentricities, and orbital resonances provide evidence for planetary migration subsequent to formation. Inward, and sometimes, outward migration as a result of interactions between the planet and the gas and residual planetesimal disk, along with planet–planet scattering, provides a compelling picture of the diversity of planetary system architectures observed. For planets that arrive to within  $\sim 0.2$  au of the host star, whether by migration or scattering, tidal effects become significant, circularising orbits, synchronising their rotation and orbital periods, and providing an additional source of internal heating.

**Interiors and atmospheres** Chapter 11 reviews the current knowledge of interiors and atmospheres, deduced primarily from the masses and densities measured for transiting planets, combined with theoretical models based on the equations of hydrostatic and thermodynamic equilibrium. Thermal equilibrium and condensation calculations can predict which chemical



species will be present for a given initial elemental composition and, from these, insight is being gained into their internal structures and atmospheric compositions.

For terrestrial-mass planets, estimates of the habitable zone, where liquid water could be present, are providing pointers to the first planets which may be habitable. The chapter includes some details of spectroscopic indicators of life, the ongoing search for extraterrestrial intelligence, and related aspects such as the Anthropic Principle and the Fermi Paradox.

### 1.3.4 Solar system

Chapter 12 provides a selective summary of solar system properties which are closely linked to developments in exoplanet studies. Solar system observations provide important constraints on theories and properties of exoplanet formation and evolution, while developments in exoplanet formation and evolution, notably planetary migration, are offering insight into the present structure and past evolution of the solar system.

Topics covered include relevant properties of the Sun, orbital stability and planet obliquities, the origin of the Moon, of water on Earth, and of planetary satellites and rings, and the current theories of planet migration believed to have occurred in the early solar system. Taken together, combined knowledge of exoplanets and the solar system is providing an increasingly detailed picture of planet formation and evolution, further suggesting that the basic models of exoplanet formation, and that of the solar system, are broadly coherent.

### 1.3.5 Appendixes

Appendix A is a compilation of numerical values of relevant reference quantities. Appendix B is a summary of the principle notation used throughout the treatment. While the use of acronyms has been avoided where possible, a list of those commonly encountered in the associated literature is included.

Appendixes C–F provide a bibliography of the main classes of exoplanet detections (radial velocity, transiting, microlensing, and imaging respectively), with a brief narrative of each system and the associated literature. These aim to provide a concise picture of the main lines of research associated with each planetary systems.

### 1.3.6 Hyperlinks and online resources

The electronic (PDF) version is extensively hyperlinked although, to enhance legibility, links are not explicitly visible. Principal links are those in the table of contents, to sections, tables, figures, equations, and citations.

Citations within the text are hyperlinked to the relevant *page* of the reference bibliography. Within the bibliography, each bibliographic entry is in turn hyperlinked to the relevant ADS abstract page. In the few instances where the ADS does not include the relevant ci-

tation link (typically older or non-astronomical articles) the link points only to the ADS search page.

The reference bibliography also includes ‘back references’, linking the bibliographic item to the page(s) on which the reference was cited. These back references are also actively hyperlinked to the relevant cited page(s).

In the planet chronologies, Appendixes C–F, the host star name is hyperlinked to the host star page of the NASA Exoplanet Archive. In addition to hyperlinks to the reference bibliography, the  $\triangleright$  icon *following* the citation leads directly to the relevant ADS abstract page.

As detailed in the Preface, a number of files are available at [www.cambridge.org/exoplanethandbook](http://www.cambridge.org/exoplanethandbook).

## 1.4 Astronomical terms and units

A summary of key astronomical terms and nomenclature is provided for those with less familiarity of the field.

**Astronomical terms** Various relevant terms used in astronomy and planetary science may cause some confusion on first encounter. More detailed explanations are given in appropriate places in the text, but advanced warning of some of these may assist orientation.

*Metallicity*: in astronomy usage, the term ‘metal’ is divorced from its usual chemical definition related to electrical conductivity and chemical bonding, and instead refers collectively to all elements other than H or He (and essentially therefore to the elements produced by nucleosynthesis in stars or supernovae).

*Ice, gas, and rock*: in planetary science, ‘ices’ refer to volatile materials with a melting point between  $\sim 100$ – $200$  K. In consequence, ‘ices’ (for example in Uranus and Neptune) are not necessarily  $\text{H}_2\text{O}$ , not necessarily ‘cold’, and not necessarily solid. Similarly, a ‘gas’ in planetary science is not defined by phase, but rather as a highly volatile material with a melting point (if at all) below  $\sim 100$  K. ‘Rock’ may be defined by its solid phase or present mineralogical composition, but generally also by its presumed chemical composition and highly refractory nature during the epoch of planetary formation.

**Notation for star and planet parameters** Stars and planets are characterised, amongst other parameters, by their mass  $M$  and radius  $R$ , with subscripts  $\star$  and  $p$  referring to star and planet respectively, and the distance to the system  $d$ .

Masses and radii of stars are usually expressed in solar units ( $M_\odot, R_\odot$ ), while those of planets are typically expressed in either Jupiter units ( $M_J, R_J$ ) for the more massive, or Earth units ( $M_\oplus, R_\oplus$ ) for planets closer to terrestrial mass. Numerical values (and sources) for these and other quantities are given in Appendix A.

Orbits are primarily characterised by their period  $P$ , semi-major axis  $a$ , eccentricity  $e$ , and inclination with respect to the plane of the sky  $i$  ( $i = 0^\circ$  face-on,  $i = 90^\circ$  edge-on). Further details are given in §2.1.1.

**Nominal conversion constants** Given that neither the solar nor the planetary masses and radii are secularly constant, and that their instantaneous values are being determined ever more precisely, IAU (2015) Resolution B3 recommended nominal conversion constants for selected solar and planetary (Earth/Jupiter) properties (Mamajek et al., 2015b). The motivation is that their consistent use in relevant formulae and models (and employing the recommended notation which, however, is not used here), would guarantee a uniform conversion to SI units. These recommended values are consistent with the solar system ephemerides values in Appendix A, and with the IAU 2009 system of astronomical constants (Luzum et al., 2011).

Thus the IAU nominal (N) equatorial (e) and polar (p) radii for Earth and Jupiter (at a pressure of 1 bar  $\equiv 10^5$  Pa) are

$$1\mathcal{R}_{eE}^N = 6.3781 \times 10^6 \text{ m} \quad 1\mathcal{R}_{pE}^N = 6.3568 \times 10^6 \text{ m} \quad (1.1)$$

$$1\mathcal{R}_{ej}^N = 7.1492 \times 10^7 \text{ m} \quad 1\mathcal{R}_{pj}^N = 6.6854 \times 10^7 \text{ m} \quad (1.2)$$

If the equatorial or polar radius is not explicitly specified, the former is to be understood. The *de facto* definition of  $R_j$  in terms of Jupiter's equatorial radius at  $10^5$  Pa means that, due to its oblateness, Jupiter's mean radius is actually  $0.978R_j$ .

**Star distances and masses** Stellar distances are given in *parsec* (pc). As the basic unit of astronomical distance based on measurements of trigonometric parallax, this is the distance at which the mean Sun–Earth distance (the astronomical unit, or au; Appendix A) subtends an angle of 1 arcsec (1 pc  $\approx 3.1 \times 10^{16}$  m  $\approx 3.26$  light-years).

For orientation, distances to the nearest stars are of order 1 pc; there are about 2000 known stars within 25 pc of the Sun. With the exception of microlensing events, most exoplanet discoveries and detections are restricted to a distance horizon of order 50–100 pc.

In general, stellar masses range from  $\sim 0.1 - 30 M_\odot$ , with spectral types providing a conventional classification related to the primary stellar properties of temperature and luminosity. The Sun is of spectral type G2V, with a main-sequence (H-burning) life time around 9 Gyr: cooler stars (types K, M) are of lower mass and have longer lifetimes; hotter stars (types F, A, etc.) are of higher mass and have shorter lifetimes. Stellar masses of interest to exoplanet studies are typically in the range  $0.1 - 5 M_\odot$ , with the majority of targets and detections focused on masses rather close to  $1 M_\odot$ .

**Star names** Details of the naming conventions of celestial objects, ratified by the IAU Commission 5 Working Group on Designations, are given at the URL in Table 1.4.

Object names such as 70 Vir (for 70 Virginis) and  $\beta$  Pic (for  $\beta$  Pictoris) reflect constellation-based nomenclature, while others reflect catalogues or techniques labeled with running numbers (e.g. HD 114762) or coordinates (e.g. PSR B1257+12). Some of the most commonly referenced star catalogues of relevance are:

*HD (Henry Draper)*: surveyed by Cannon & Pickering (Ann. Astr. Obs. Harvard, Vol. 91–99, 1918–1924).

*HIP (Hipparcos)*: the space-based astrometric catalogue extends to  $\approx 12$  mag, but with a completeness between

**Exoplanet names:** Various alternative naming schemes have been proposed, none having gained wider support.

A few planets have been given unofficial epithets (by their discoverers or others): Bellerophon  $\equiv 51$  Peg b (Lyra, 2010); Osiris  $\equiv$  HD 209458 b (Vidal-Madjar et al., 2008); Tatooine  $\equiv$  Kepler–16(AB) b (the fictional planet orbiting two suns in Star Wars); Zarmina  $\equiv$  GJ 581 g (Vogt et al., 2010a); Methuselah  $\equiv$  PSR B1620–26 b (for its extreme age); and Einstein's planet  $\equiv$  Kepler–76 b (Faigler et al., 2013).

Lyra (2010) proposed constellation-based names mostly drawn from Roman–Greek mythology for the 403 planets known in October 2009; those in Pegasus included Bellerophon (51 Peg b), Minerva (HD 209458 b), Nike (HAT–P–8 b), and Parthenos (WASP–10 b).

A more quantitative 4-parameter taxonomic classification, intended to be easily interpreted whilst conveying the most relevant planetary information, was proposed by Plávalová (2012). It qualifies planet mass in terms of solar system masses (m/E/N/J), logarithmic semi-major axis, mean temperature [F(reezing), W(ater), G(aseous), R(oaster), and P(ulsar)], and orbital eccentricity.

The International Astronomical Union (IAU) originally stated that it had no plans to assign names to extrasolar planets, considering that *‘if planets are found to occur very frequently in the Universe, a system of individual names might well rapidly be found impracticable’*. Nonetheless, in July 2014, it initiated a process to assign names to certain systems, via public nomination ([www.iau.org/public/themes/naming\\_exoplanets](http://www.iau.org/public/themes/naming_exoplanets)). In December 2015, for example, the IAU announced the winning names for the PSR B1257+12 pulsar system: Lich for the pulsar, with Draug, Poltergeist and Phobetor for its planets.

Other commercially-oriented naming websites exist.

7.3–9.0 mag depending on Galactic latitude and spectral type (Perryman et al., 1997a, see §8.1.1).

*BD (Bonner Durchmusterung)*: the BD was the first of the 3-part Durchmusterung (German for survey) covering the entire sky. The northern sky was surveyed from Bonn by Argelander & Schönfeld and published between 1852–1859. The extension southwards was surveyed from Córdoba, Argentina (Córdoba Durchmusterung, or CD) by Thomme starting in 1892. The southern skies were surveyed from the Cape of Good Hope (Cape Durchmusterung, or CPD) by Gill & Kapteyn around 1900. Stars tend to be assigned their DM (Durchmusterung) number if they are not in the HD or HIP catalogues.

*Nearby stars*: if included in the Catalogue of Nearby Stars (CNS; §8.1.3), they are designated in the CDS SIMBAD database as GJ nnn. The deprecated alternatives Gliese nnn or Gl nnn are sometimes encountered.

*Alternative designations*: alternative exoplanet host star designations are often encountered, especially until some consensus designation has been adopted. Thus some early studies referred to 55 Cnc as HR 3522 or  $\rho^1$  Cnc; HIP 75458 as  $\iota$  Dra or HD 137759; HR 810 as  $\iota$  Hor or HD 17051; etc. The CDS SIMBAD facility (Table 1.4) provides full cross-identifications.

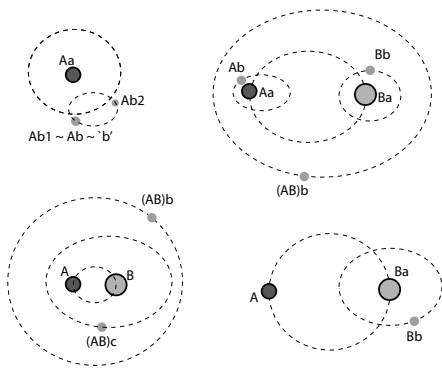


Figure 1.4: Exoplanet name suffixes for single and binary systems following Hessman et al. (2010). Upper left: planet around a single star plus a moon. Upper right: binary star, each with a planet (e.g. HD 41004), plus a circumbinary planet. Lower left: two circumbinary planets (e.g. NN Ser). Lower right: planet around the secondary star in a binary (e.g. HD 178911). From Hessman et al. (2010, Figure 1).

**Coordinate designation:** coordinate-based designations for (typically fainter) sources from catalogues such as 2MASS and SDSS are detailed on page 432.

**Kepler targets:** Kepler mission targets may be referred to by their confirmed Kepler–NNN identifier, or by their KIC or KOI identifiers, depending on validation status (box, page 175). This work adopts the Kepler–NNN identifier where assigned. The NASA Exoplanet Archive (Table 1.4) provides cross-identifications, along with the default identifier.

**Exoplanet identifiers** The *de facto* custom denotes planets around star X as X b, c,... lexically according to discovery sequence (rather than, for example, according to mass or semi-major axis, which would demand constant revision as additional planets are discovered).

Nomenclature for planets in binary star systems, following Hessman et al. (2010), is illustrated in Figure 1.4.

The convention for microlensing planets, where the host star is generally invisible, is described on page 142.

**Exomoon identifiers** If and when exomoons are discovered, they are likely to be designated with post-fixed Roman numerals, following the convention for solar system satellites (cf. box, page 689). This has already been adopted for the exomoon candidate Kepler–1625 b I, identified by Teachey et al. (2018).

**Units** In aiming for a consistent usage of terms and nomenclature, units referred to in the published literature have occasionally been unified. Usage here follows, as far as is considered reasonable, the International System of Units (SI), including the SI prefixes for multiples of  $10^3$ ,  $10^6$  and  $10^9$  as k, M, and G.

Astronomical measures of density generally use the non-SI unit of  $\text{g cm}^{-3}$ . Densities here are expressed in units of  $\text{Mg m}^{-3}$ , conforming to SI, and with the same numerical values (and same number of keystrokes).

Characterisation of pressure, notably in the description of planetary atmospheres and interiors, is divided in the literature between the SI pascal,  $1\text{ Pa} \equiv 1\text{ Nm}^{-2}$ , and the bar ( $1\text{ bar} \equiv 10^5\text{ Pa}$ ). The latter, some 1% smaller than ‘standard’ atmospheric pressure, is not an SI unit, although it is accepted for use within SI. For uniformity, Pa is used preferentially here.

Various units outside of SI are accepted for use, or are consistent with the recommendations of the International Committee for Weights and Measures (CIPM, *Comité International des Poids et Mesures*). These include the measurements of time as minute (min), hour (h), and day (d), and the measurement of angles in seconds of arc: units of arcsec, mas (milli-arcsec) and  $\mu\text{as}$  (micro-arcsec) are used accordingly.

The IAU (1989) system of astronomical constants recommended the symbol ‘a’ for Julian year. This treatment follows wider astronomical convention in using ‘yr’ when the distinction of Julian year is unwarranted.

Specification of geological time (Chapter 12) faces the issue that, with SI adherence being less critical, a distinction is nonetheless often useful between geohistorical *duration*, and geohistorical *date*. This treatment follows the widespread (and recommended, Aubry et al., 2009) practice in geological science of expressing durations in years, symbol ‘yr’ (with multiples kyr, Myr, and Gyr); with dates (in years before present, or BP) denoted as ‘annus’, symbol ‘a’ (with multiples ka, Ma, and Ga).

Certain units central to astronomy, notably those of mass and radius noted above, deviate from SI, but are retained in this treatment. The astronomical unit is accepted within the SI; following the IAU (2012) recommendation, it is indicated here as ‘au’.

**A, AU, ua, au** The IAU (1976) system of astronomical units used the symbol ‘A’ for the astronomical unit. In 2006, the International Bureau of Weights and Measures (BIPM), which reports to the CIPM, recommended use of ‘ua’, which was followed in the non-normative Annex C to ISO 80000–3 (2006). However, ‘AU’ continued as a common abbreviation. In 2012, the IAU recommended the use of ‘au’. This was adopted in the BIPM’s 2014 revision of the SI Brochure, and since by the major journals.

**Mathematical notation** A compilation of the adopted notation is given in Appendix B. For the designation of parallax, the symbol  $\varpi$  is widely used in the astrometric literature and is employed here (rather than the frequently used  $\pi$ ), to avoid confusion with the mathematical constant with which it frequently appears.

**North, south, east, west, morning, evening** These terms, used in the context of atmospheric ‘general circulation models’ (§11.4.2), merit some explanation.

Earth’s north pole being so denoted by convention, and its orbit about the Sun being prograde (in the same sense as its rotation), it rotates counter-clockwise when viewed from above its north pole. Its rotation from west to east, with the morning Sun perceived to ‘rise’ in the east, defines these concepts.

On Earth, winds termed ‘easterly’ or ‘westerly’ conventionally designate the direction from which they originate, viz. ‘easterly’ when they blow *from* the east (i.e. towards the west, or *westward*), and *vice versa* (although in other contexts, and potentially confusingly, reference may be made to an ‘easterly’ or ‘westerly’ *direction*). Earth’s atmospheric circulation is characterised by prevailing equatorial *easterly* winds (box, page 594), while highly irradiated hot Jupiters are generally distinguished by equatorial prograde (westerly) winds, carrying energy from stellar irradiation *eastward* from the sub-stellar point, thereby signifying an atmosphere which is ‘superrotating’ (§11.4.2).

For other solar system bodies, the IAU Working Group on Cartographic Coordinates and Rotational Elements defines the geographic north pole of a planet (or satellite) as that in the same celestial hemisphere relative to the solar system’s invariable plane as Earth’s north pole (Archinal et al., 2011). An object’s direction of rotation is then termed positive (prograde) if it rotates counter-clockwise when viewed from above its north pole, and negative (retrograde) if it rotates clockwise.

Compounded by the large inclination of the ecliptic, the IAU Working Group extends its definition to cases (e.g. Uranus) where the declination of a pole relative to Earth’s celestial equator could be negative, even though a planet’s north pole is north of the invariable plane; and to some minor bodies (e.g. comet 2P/Encke) where the poles precess rapidly enough to reverse over a few decades using the invariable plane definition.

Planetary *coordinate systems* are defined relative to their mean axis of rotation. The longitude systems of most solar system bodies with observable rigid surfaces are defined by reference to some surface feature, such as a crater.

For exoplanets, east and west are similarly defined in terms of an (assumed) prograde rotation (defined in terms of sidereal rotation for a tidally locked planet). As a result, even though hot Jupiters are spatially unresolved, a peak brightness generally observed to be temporally in advance of the secondary eclipse implies an *eastward*-shifted hot spot. Given such advected heat flow, the western terminator (dividing day- and night-sides) is also frequently referred to as the ‘dawn terminator’, or ‘morning side’ (being cooler), while the eastern terminator is also referred to as the ‘dusk’ or ‘evening’ terminator (being hotter).

## 1.5 Definition of a planet

**Background: IAU 2003 recommendation** The IAU 2003 recommendation, by the working group on extra-solar planets (IAU, 2003) is, verbatim:

(1) objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be  $13M_J$  for objects of solar metallicity) that orbit stars or stellar remnants are *planets* (no matter how they formed). The minimum mass required for an extra-solar object to be considered a planet should be the same as that used in the solar system;

(2) substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are *brown dwarfs*, no matter how they formed nor where they are located;

(3) free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not planets, but are *sub-brown dwarfs* (or whatever name is most appropriate).

**Background: IAU 2006 resolution** In its resolution B5 (IAU, 2006), the IAU classified the solar system bodies into three distinct categories (verbatim):

(1) a *planet* is a celestial body that: (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit;

(2) a *dwarf planet* is a celestial body that: (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (c) has not cleared the neighbourhood around its orbit, and (d) is not a satellite;

(3) other objects except satellites orbiting the Sun are referred to collectively as *small solar system bodies*.

This classification, which excludes Pluto as a planet under criterion 1(c), is nevertheless recognised as being somewhat ambiguous due to the difficulties in formulating precise definitions of shape and orbital ‘clearing’.

**Adopted convention** Attempts to formulate a precise definition of a planet are confronted by a number of difficulties (e.g. Basri & Brown, 2006). At the upper mass range, definitions according to formation scenario, or according to mass, encounter problems if these two definitions do not coincide. Chabrier et al. (2014) argued that the IAU definition for distinguishing planets from brown dwarfs on the basis of deuterium burning ‘*has no physical justification and results in scientific confusion*’. At the lower mass range, classification is presently facilitated by the fact that a distinction in mass between exoplanets and smaller bodies is not yet relevant.

A definition dispensing with upper and lower mass limits is suggested by Soter (2006): *A planet is an end product of disk accretion around a primary star or sub-star*. In this case, the upper mass limit for a planet is probably in the range  $25\text{--}30M_J$ , rather than  $13M_J$ . There is presumably no reason why a ‘planet’ could not form in this way, and burn its deuterium. Indeed, Schneider et al. (2011) assigned a mass of  $25M_J$  as the upper limit for including objects in the Exoplanet Encyclopaedia. An illustrative case is the 2-planet system HD 168443 (Marcy et al., 1999, 2001b; Udry et al., 2002; Pilyavsky et al., 2011), in which planet b ( $M_p \sin i = 8.2M_J$ ) and planet c ( $M_p \sin i = 18.1M_J$ ) lie below and above the deuterium-burning threshold respectively, but presumably have a common (disk-accretion) origin.

Hatzes & Rauer (2015) proposed a definition based on changes in slope of the  $\log M\text{--}\log \rho$  relation (§11.5.4). By this criterion, objects with  $M_p \lesssim 0.3M_J$  are low mass planets, either icy or rocky. Giant planets cover the range  $0.3\text{--}60M_J$ , with objects of a few  $M_J$  considered as ‘low mass giant planets’, while those at the upper end of the giant planet sequence (brown dwarfs) referred to as ‘high mass giant planets’.

In this treatment, isolated objects are referred to as sub-brown dwarfs or brown dwarfs according to whether they lie below or above the deuterium-burning threshold, and (generally) only as ‘free-floating planets’ if evidence suggests that such a label is appropriate.

## 1.6 Planet categories

With more than 3500 planets known by the end of 2017, various attempts have been made to classify them. This section provides an introduction to the classes of planets being discovered, in anticipation of the following discussions of their discovery and theories of their formation.

### 1.6.1 Classification by size or mass

**Planet size** As detailed in Chapter 6, the key observable for transiting planets is its (relative) size (rather than mass). Borucki et al. (2011b) adopted the categories:

- Earth-size, or terrestrial planets ( $< 1.25R_{\oplus}$ ),
- super-Earth-size ( $1.25 - 2R_{\oplus}$ ),
- Neptune-size ( $2 - 6R_{\oplus}$ ), and
- Jupiter-size ( $6 - 15R_{\oplus}$ ).

These are not universally-accepted ‘definitions’, and other boundaries have been adopted (e.g. Morbidelli & Raymond (2016) consider super-Earths as  $R_p < 4R_{\oplus}$  and  $P < 100$  d), but represent an indicative classification.

**Planet mass** For radial velocity or microlensing planets, the key relevant observable is (projected) planet mass. Including a distinction between Earths and super-Earths at  $2M_{\oplus}$  (cf.  $1.9M_{\oplus}$  defined by Charbonneau et al. 2009, roughly equivalent to  $2R_{\oplus}$ ; and  $1M_{\oplus}$  by Valencia et al. 2007b), the classification proposed by Stevens & Gaudi (2013, see Figure 1.5) is:

- sub-Earths ( $10^{-8}M_{\oplus} - 0.1M_{\oplus}$ ),
- Earths ( $0.1M_{\oplus} - 2M_{\oplus}$ ),
- super-Earths ( $2M_{\oplus} - 10M_{\oplus}$ ),
- Neptunes ( $10M_{\oplus} - 100M_{\oplus}$ ),
- Jupiters ( $100M_{\oplus} - 10^3M_{\oplus}$ ),
- super-Jupiters ( $10^3M_{\oplus} - 13M_J$ ),
- brown dwarfs ( $13M_J - 0.07M_{\odot}$ ), and
- stellar companions ( $0.07M_{\odot} - 1M_{\odot}$ ).

Again, these are not universally-accepted ‘definitions’, and other boundaries have been adopted.

**Statistics** As of the end of 2017, the NASA Exoplanet Archive listed 3572 planets in nearly 600 multiple systems. Table 1.3 shows those that have mass or radius estimates. Some miscellaneous ‘quantities of interest’ are given in Table 1.5, and some ‘extreme’ transiting and radial velocity systems are listed in Table 1.6.

### 1.6.2 Giant planets

Despite widespread references to ‘giant planets’, a precise definition is not straightforward. In the context of

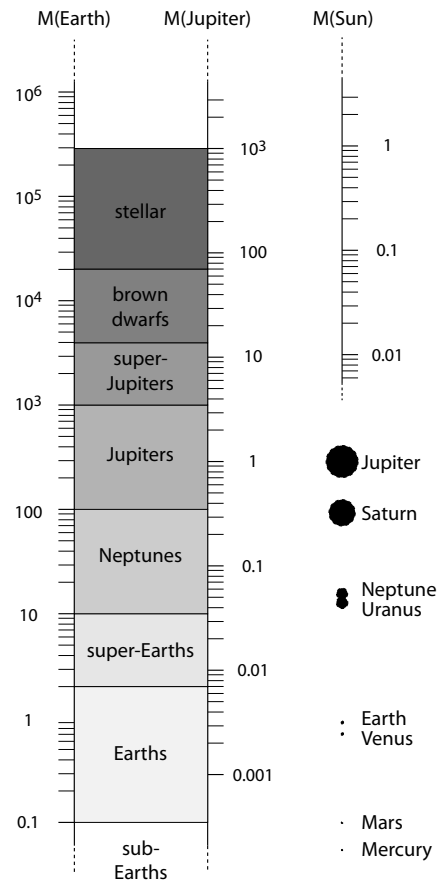


Figure 1.5: The classification of planet masses according to solar system objects, following the proposal by Stevens & Gaudi (2013). Masses of the solar system planets are shown at the right, with a circle size proportional to planet radius.

the steep mass function implied by microlensing surveys, Clanton & Gaudi (2014b) defined giant planets as having  $>50\%$  H–He by mass, which, in the core accretion paradigm, would imply that their cores must have reached critical mass before gas disk dispersal.

They define a ‘minimum’ giant planet mass of  $0.1M_J \sim 30M_{\oplus}$ , since planets with  $M_p \geq 0.1M_J$  are likely composed of  $>50\%$  H and He by mass, unless their protoplanetary disk was very massive (and thus the isolation mass was large) or the heavy element content was  $\gg 10\%$ . Counter examples might include HD 149026 b (Sato et al., 2005a; Carter et al., 2009), which is believed to have a highly metal-enriched composition, probably  $>50\%$  heavy elements by mass.

In comparison (cf. §12.2.2), Jupiter and Saturn ( $\sim 0.3M_J$ ) primarily comprise H and He, while Neptune ( $\sim 0.05M_J$ ) and Uranus ( $\sim 0.05M_J$ ) contain roughly 5–15% H and He, 25% rock, and 60–70% ices, by mass, assuming the ice-to-rock ratio is protosolar (Podolak et al., 1991, 1995; Hubbard et al., 1995; Guillot, 2005).

Table 1.2: A selective (and subjective) chronology of exoplanet discoveries, including the first discoveries of some major instruments. Ordering is by received date of the published journal article. Theoretical contributions are (generally) not included.

Date	Subject	Reference
1987-12-14	Possible $1.7M_J$ radial velocity planet (later confirmed): $\gamma$ Cep	Campbell et al. (1988)
1989-01-18	Possible $11M_J$ radial velocity planet (later confirmed): HD 114762	Latham et al. (1989)
1991-11-21	Multiple planet system from radio timing of millisecond pulsar: PSR B1257+12	Wolszczan & Frail (1992)
1992-12-10	Possible $2.9M_J$ radial velocity planet (later confirmed): HD 62509	Hatzes & Cochran (1993)
1995-08-29	Radial velocity planet #1 (OHP–ELODIE): $0.47M_J$ , $P = 4.2$ d): 51 Peg	Mayor & Queloz (1995)
1996-01-22	Radial velocity planet #2 (Lick: $6.6M_J$ , $P = 117$ d): 70 Vir	Marcy & Butler (1996)
1996-02-15	Radial velocity planet #3 (Lick: $2.4M_J$ , $P = 2.98$ yr): 47 UMa	Butler & Marcy (1996)
1999-11-12	Photometric transit of a known planet (0.8-m APT): HD 209458	Henry et al. (1999)
1999-11-19	" (0.1-m STARE): HD 209458	Charbonneau et al. (2000)
1999-11-15	First (six) planets detected with Keck–HIRES	Vogt et al. (2000)
2000-01-03	Measurement of Rossiter–McLaughlin effect (ELODIE): HD 209458	Queloz et al. (2000a)
2000-12-27	System in (2:1) mean motion resonance (Lick/Keck): GJ 876 b and c	Marcy et al. (2001a)
2002-05-03	'Free-floating' cluster object of planet mass (sub-brown dwarf): S Ori 70	Zapatero Osorio et al. (2002)
2002-11-27	First planet discovered by transit photometry surveys (OGLE): OGLE–TR–56	Konacki et al. (2003a)
2002-12-11	Dust disk around white dwarf attributed to disrupted asteroid: G29–38	Jura (2003)
2003-12-23	Atmospheric (escaping) H I, O I, C II detected (HST–STIS): HD 209458 b	Vidal-Madjar et al. (2004)
2004-02-12	Microensing planet #1 (confirmed, $2.6M_J$ ): OGLE–2003–BLG–235L b	Bond et al. (2004)
2004-03-04	First planet detected with HARPS (radial velocity): HD 330075 b	Pepe et al. (2004a)
2004-08-06	First planet discovered by bright star transit photometry surveys: TrES–1 b	Alonso et al. (2004)
2004-10-06	Imaging of borderline planet/brown dwarf companion (VLT–NACO): GQ Lup	Neuhäuser et al. (2005)
2004-11-19	Probable planet detected by imaging (later confirmed): Fomalhaut	Kalas et al. (2005)
2005-02-03	Thermal emission (secondary eclipse) detected by Spitzer: TrES–1 b	Charbonneau et al. (2005)
2005-02-03	" " HD 209458 b	Deming et al. (2005b)
2005-04-05	Imaging of planet ( $4M_J$ ) around brown dwarf (VLT–NACO): 2M J1207 b	Chauvin et al. (2005a)
2005-05-20	Microensing planet #2 ( $3.8M_J$ ): OGLE–2005–BLG–71	Udalski et al. (2005)
2005-05-24	Low-mass planet $< 10M_{\oplus}$ ( $6 - 8M_{\oplus}$ ): GJ 876 d	Rivera et al. (2005)
2005-09-28	Low-mass microensing planet ( $5.5M_{\oplus}$ ): OGLE–2005–BLG–390L b	Beaulieu et al. (2006)
2006-02-13	Astrometric confirmation of radial velocity detection (HST–FGS): $\epsilon$ Eri b	Benedict et al. (2006)
2006-03-10	System with three $5 - 20M_{\oplus}$ planets (HARPS): HD 69830	Lovis et al. (2006)
2006-08-12	First transiting planet from HATNet: HAT–P–1 b	Bakos et al. (2007b)
2006-08-15	Detection of day/night variation in thermal emission (Spitzer): $\nu$ And b	Harrington et al. (2006)
2006-09-22	First transiting planets from SuperWASP: WASP–1 b and WASP–2 b	Collier Cameron et al. (2007a)
2006-10-05	Planet in an open cluster (Hyades giant, Okayama): $\epsilon$ Tau b	Sato et al. (2007)
2006-10-24	Zeeman–Doppler imaging of a host star magnetic field: $\tau$ Boo	Catala et al. (2007)
2006-12-06	First determination of transiting planet absolute obliquity, $\psi$ : HD 189733 b	Winn et al. (2007c)
2006-12-20	Planet around a K giant (Tautenburg): 4 UMa	Döllinger et al. (2007)
2007-01-19	Infrared spectrum (Spitzer–IRS): HD 189733 b	Grillmair et al. (2007)
2007-02-08	Atmospheric superrotation inferred from Spitzer: HD 189733 b	Knutson et al. (2007a)
2007-04-04	Super-Earth planet ( $7.7M_{\oplus}$ ) in the habitable zone (HARPS): GJ 581 c	Udry et al. (2007)
2007-04-06	Planet detected in timing of $p$ -mode pulsator: V391 Peg b	Silvotti et al. (2007)
2007-04-08	Atmospheric $H_2O$ detected (Spitzer–IRAC): HD 189733 b	Tinetti et al. (2007b)
2007-05-08	System with five planets (from 18-yr radial velocity): 55 Cnc	Fischer et al. (2008)
2007-10-04	Long-period transiting planet (21.2 d): HD 17156 b	Barbieri et al. (2007)
2007-10-17	Planet candidate detected in timing of white dwarf: GD 66 b	Mullally et al. (2008)
2007-10-19	Microensing 2-planet system with orbital motion: OGLE–2006–BLG–109L b/c	Gaudi et al. (2008)
2007-10-22	Detection of polarised light variations during transit: HD 189733 b	Berdyugina et al. (2008)
2008-01-04	First planet detected by CoRoT (space photometry): CoRoT–1 b	Barge et al. (2008)
2008-08-07	Planet detected in timing of eclipsing binary (previously suspected): HW Vir	Lee et al. (2009)
2008-09-07	Atmospheric $CO_2$ , CO, $H_2O$ detected (HST–NICMOS): HD 189733 b	Swain et al. (2009c)
2008-09-30	Planet detected by imaging (HST–ACS): Fomalhaut	Kalas et al. (2008)
2008-09-30	Three planets detected by imaging (Keck/Gemini): HR 8799	Marois et al. (2008b)
2008-11-10	Probable planet detected by imaging, later confirmed (VLT–NACO): $\beta$ Pic	Lagrange et al. (2009b)
2009-01-28	Secondary eclipse detection by CoRoT: CoRoT–7 b	Snellen et al. (2009a)
2009-02-23	Transiting super-Earth ( $3 - 10M_{\oplus}$ ) in 2-planet system: CoRoT–7 b	Léger et al. (2009)
2009-03-04	Short-period planet with evidence for tidal decay: WASP–18	Hellier et al. (2009a)
2009-03-24	Low-mass planet $< 2M_{\oplus}$ ( $1.9M_{\oplus}$ , HARPS): GJ 581 e	Mayor et al. (2009a)
2009-07-20	First transiting planet system known to be multiple: HAT–P–13 b/c	Bakos et al. (2009b)
2009-08-12	Possible retrograde orbit (later confirmed): HAT–P–7 b	Winn et al. (2009d)
2009-10-14	Relative orbit inclinations from astrometry (HST–FGS): $\nu$ And c/d	McArthur et al. (2010)
2009-10-20	Super-Earth planet ( $6.5M_{\oplus}$ ) transiting an M star (MEarth): GJ 1214 b	Charbonneau et al. (2009)

Table 1.2. A selective chronology of exoplanet discoveries (cont., 2/3).

Date	Subject	Reference
2009-11-02	Spectrum of an imaged planet (VLT-NACO): HR 8799 c	Janson et al. (2010)
2009-11-15	Detection of ellipsoidal variations: HAT-P-7	Welsh et al. (2010)
2009-11-16	First transiting planet detected by Kepler (space photometry): Kepler-4 b	Borucki et al. (2010b)
2010-02-04	Planet orbit from CO in VLT-CRILES transmission spectrum: HD 209458 b	Snellen et al. (2010a)
2010-02-17	Triple (Laplace) resonance (Keck-HIRES): GJ 876 b, c, e	Rivera et al. (2010b)
2010-04-21	Short-period ( $\delta$ Scuti) planet with tidal excitation of stellar pulsations: WASP-33	Collier Cameron et al. (2010b)
2010-07-08	First exoplanet discovered by astrometry (unconfirmed): HD 176051 b	Muterspaugh et al. (2010b)
2010-07-13	Retrograde orbit suggested for possible circumprietary planet: $\nu$ Oct b	Eberle & Cuntz (2010)
2010-07-28	System with two transiting planets with timing variations: Kepler-9 b/c	Holman et al. (2010)
2010-07-29	Planets detected in a sample of 104 metal-poor stars	Santos et al. (2011)
2010-08-09	Ellipsoidal and relativistic beaming effects in transit light curve: CoRoT-3	Mazeh & Faigler (2010)
2010-08-12	System with (possibly) seven planets (HARPS): HD 10180	Lovis et al. (2011)
2010-09-01	Inferred gas-driven migration in the solar system: the Grand Tack model	Walsh et al. (2011)
2010-09-03	Fourth (Jupiter-like) planet around $\nu$ And	Curiel et al. (2011)
2010-09-06	Sodium D lines and $T - P$ profile in the upper atmosphere of HD 209458 b	Vidal-Madjar et al. (2011)
2010-10-04	Mass constraints from Hipparcos astrometry: nine confirmed planets	Reffert & Quirrenbach (2011)
2010-10-17	A $7M_J$ planet orbiting the binary cataclysmic variable DP Leo	Beuermann et al. (2011)
2010-10-25	Near-grazing transiting planet in a hierarchical triple system: WASP-34 b	Smalley et al. (2011a)
2010-11-05	Fourth planet imaged in the HR 8799 system	Marois et al. (2010)
2010-11-10	First Kepler rocky planet ( $\rho = 8.8 \text{ Mg m}^{-3}$ ) and seismology: Kepler-10 b	Batalha et al. (2011)
2010-12-13	Six low-mass transiting planets in a closely-packed system: Kepler-11	Lissauer et al. (2011a)
2010-12-15	Retrograde orbit of HAT-P-6 b	Hébrard et al. (2011a)
2011-01-24	Near-grazing transit: HAT-P-27 b (WASP-40 b)	Anderson et al. (2011a)
2011-02-02	65 transit timing variation candidates from the first 4 months of Kepler data	Ford et al. (2011)
2011-03-04	Terrestrial-mass planet in the habitable zone: GJ 581 d	Wordsworth et al. (2011)
2011-03-19	Transiting hot Jupiter in a highly oblique orbit: HAT-P-30 b	Johnson et al. (2011c)
2011-04-09	Confirmation of Kepler-10 c through Spitzer secondary eclipse observations	Fressin et al. (2011)
2011-04-14	Very close orbiting hot Jupiter ( $a = 0.014 \text{ au}$ ): WASP-43 b	Hellier et al. (2011b)
2011-04-27	55 Cnc e found to be transiting by the MOST satellite	Winn et al. (2011c)
2011-06-07	Bow shock inferred from early transit ingress in the near-ultraviolet: WASP-12 b	Llama et al. (2011)
2011-06-10	Microlens parallax with the EPOXI spacecraft: MOA-2009-BLG-266L b	Muraki et al. (2011)
2011-07-06	Two-planet compact system which survived the red giant phase: Kepler-70	Charpinet et al. (2011)
2011-07-06	Pronounced example of rotationally-modulated star spots with Kepler: HAT-P-11	Sanchis-Ojeda & Winn (2011)
2011-07-25	Obliquity from stroboscopic star spots: Kepler-17	Désert et al. (2011b)
2011-08-17	A $3.6M_{\oplus}$ planet at the inner edge of the habitable zone: HD 85512	Pepe et al. (2011)
2011-08-18	Beaming, ellipsoidal and reflection modulation: Kepler-13 b	Mazeh et al. (2012)
2011-08-19	Long deep eclipses attributed to a circumstellar disk system: 1SWASP J1407	Mamajek et al. (2012)
2011-09-01	Multiple planets confirmed from transit timing variations: Kepler-23 and 24	Ford et al. (2012a)
2011-09-01	Four transiting planets in a 3:4:6:8 resonance chain: Kepler-223	Fabrycky et al. (2011)
2011-09-07	Rossiter-McLaughlin effect from host star chromosphere: CoRoT-2A	Czesla et al. (2012)
2011-09-08	X-ray activity phased with planet motion: HD 189733	Pillitteri et al. (2011)
2011-09-12	37 new HARPS (radial velocity) planets, amongst which 15 super-Earths	Mayor et al. (2011)
2011-09-15	First circumbinary ( $P = 41 \text{ d}$ ) transiting planet: Kepler-16(AB) b	Doyle et al. (2011)
2011-10-11	Enhanced chromospheric activity in stars with close-in planets	Krejčová & Budaj (2012)
2011-10-24	First transiting planet orbiting a pre-main sequence (T Tauri) star: PTFO 8-8695	van Eyken et al. (2012)
2011-11-08	Five-planet transiting system including 0.87 and $1.03R_{\oplus}$ : Kepler-20	Fressin et al. (2012b)
2011-11-15	Circumbinary transiting planets #2 and #3: Kepler-34(AB) b and Kepler-35(AB) b	Welsh et al. (2012)
2011-11-17	Orbital motion from planet reflected light spectroscopy (in CO): $\tau$ Boo b	Brogi et al. (2012b)
2011-11-18	First Kepler habitable zone planet, $2.4R_{\oplus}$ around a Sun-like star: Kepler-22 b	Borucki et al. (2012)
2011-11-28	Laser frequency comb observations at $0.01 \text{ m s}^{-1}$ precision: HD 75289	Wilken et al. (2012)
2011-12-04	Three-planet system comprising 0.78, 0.73, $0.57R_{\oplus}$ : Kepler-42	Muirhead et al. (2012b)
2011-12-05	Confirmation of four multi-planet systems via transit timing variations	Fabrycky et al. (2012)
2011-12-09	Anti-correlated transit timing variations in four Kepler systems	Steffen et al. (2012a)
2012-01-10	Transit depth variations due to disintegrating planet: Kepler-1520 (KIC-12557548)	Rappaport et al. (2012)
2012-02-05	Tidal signatures in radial velocity measurements: WASP-18 b	Arras et al. (2012)
2012-02-27	1108 new candidates (2300 in total) from the first 16 months of Kepler data	Batalha et al. (2013)
2012-03-07	Short period eccentric orbit attributed to Lidov-Kozai migration: GJ 436 b	Beust et al. (2012)
2012-04-05	Nine planets suggested in the HARPS radial velocity system: HD 10180	Tuomi (2012)
2012-04-12	Two planets with comparable orbits but dissimilar density: Kepler-36	Carter et al. (2012)
2012-05-05	Orbit eccentricity from transit light curves (photo-eccentric effect): HD 17156 b	Dawson & Johnson (2012)
2012-05-25	150 new transiting planet candidates from Kepler Q1-Q6 data	Huang et al. (2013)

Table 1.2. A selective chronology of exoplanet discoveries (cont., 3/3).

Date	Subject	Reference
2012-06-07	First transiting planet from the HATSouth survey: HATS-1 b	Penev et al. (2013)
2012-06-11	Suggestion of 150 MHz radio emission: HAT-P-11	Lecavelier des Etangs et al. (2013)
2012-07-30	Hot Jupiters with transit timing variations: Kepler-485, Kepler-743, and KOI-977	Szabó et al. (2013)
2012-08-03	Earth-mass planet around the nearest stellar system (unconfirmed): $\alpha$ Cen B	Dumusque et al. (2012)
2012-08-16	27 planets in 13 systems from transit timing variations: Kepler-48 to 60	Steffen et al. (2013)
2012-08-27	First multi-planet system orbiting a binary star: Kepler-47	Orosz et al. (2012a)
2012-09-03	Debris disk resolved by Herschel around planet-hosting M dwarf: GJ 581	Lestrade et al. (2012)
2012-09-07	Planet mass from transit timing variations and radial velocity: Kepler-18	Montet & Johnson (2013)
2012-09-19	Four-planet system with a planet-planet eclipse: Kepler-89 (KOI-94)	Hirano et al. (2012a)
2012-09-20	Sub-Mercury-sized planet ( $0.30R_{\oplus}$ ): Kepler-37 b	Barclay et al. (2013b)
2012-10-14	Transiting circumbinary in a quadruple system: Kepler-64 (PH-1)	Schwamb et al. (2013); Kostov et al. (2013)
2012-10-16	Second multi-planet system from microlensing: OGLE-2012-BLG-26L b/c	Han et al. (2013b)
2012-11-06	First transiting planets in an open cluster (NGC 6811): Kepler-66 and Kepler-67	Meibom et al. (2013)
2012-11-07	Habitable zone $7M_{\oplus}$ planet in a 6-planet system: HD 40307 g	Tuomi et al. (2013a)
2012-11-15	Imaging of a $13M_{\text{J}}$ planet at 55 au: $\kappa$ And	Carson et al. (2013)
2012-11-26	Transiting hot Jupiter in a wide binary system: WASP-77A b	Maxted et al. (2013a)
2012-12-03	Planet-induced stellar gravity darkening: HAT-P-7 b	Morris et al. (2013)
2012-12-13	Gas giant around M dwarf with $\Delta F \sim 3\%$ : WASP-80	Triaud et al. (2013a)
2013-01-21	Super-Earth near the habitable zone of a Sun-like star: Kepler-69	Barclay et al. (2013a)
2013-03-13	Detection of CO and H <sub>2</sub> O from direct imaging spectroscopy: HR 8799 c	Konopacky et al. (2013)
2013-03-23	Giant planet in a polar orbit revealing a polar star spot: Kepler-63 b	Sanchis-Ojeda et al. (2013c)
2013-04-10	Optical phase curves and secondary eclipses for 8 Kepler candidates	Esteves et al. (2013)
2013-04-12	Transit timing variations of 12-hr amplitude: Kepler-88 (KOI-142)	Nesvorný et al. (2013a)
2013-04-19	Nodal precession across an oblate, gravity-darkened stellar disk: PTFO 8-8695	Barnes et al. (2013a)
2013-04-22	First planets characterised using HARPS-N: Kepler-74 and Kepler-75	Hébrard et al. (2013a)
2013-04-25	BEER effects, and evidence for atmospheric superrotation: Kepler-76	Faigler et al. (2013)
2013-04-27	Five-planet system with 1.4 and $1.6R_{\oplus}$ in the habitable zone: Kepler-62	Borucki et al. (2013)
2013-06-10	Transit detection at soft X-ray wavelengths: HD 189733 b	Poppenhaeger et al. (2013)
2013-07-09	Seven-planet transiting system, with largest transit timing variations: Kepler-90	Cabrera et al. (2014)
2013-08-14	Rapid orbit precession: Kepler-13	Szabó et al. (2014)
2013-09-25	Earth-sized planet with Earth-like density: Kepler-78	Pepe et al. (2013a); Howard et al. (2013)
2013-09-30	Resolved imaging of a debris disk with Herschel: HR 8799	Mathews et al. (2014a)
2013-10-02	Direct imaging confirmation with VLT-NACO: HD 95086 b	Rameau et al. (2013b)
2013-10-25	First hot Jupiter in the Hyades cluster, from radial velocities: HD 285507	Quinn et al. (2014)
2013-11-15	Radial velocity of non-transiting planet from transit time variations: Kepler-88	Barros et al. (2014b)
2014-01-30	Imaging of $\beta$ Pic b with Gemini Planet Imager (GPI)	Macintosh et al. (2014)
2014-05-01	Planet rotation from CO absorption: $\beta$ Pic	Snellen et al. (2014)
2014-05-24	Spin-orbit misalignment of the transiting super-Earth: 55 Cnc e	Bourrier & Hébrard (2014)
2014-06-10	Transiting Uranus-sized planet near the snow line ( $P = 704.2$ d): Kepler-421 b	Kipping et al. (2014c)
2014-06-20	Constraints on Earth-analogue plate tectonics in a white dwarf photosphere: GD 362	Jura et al. (2014)
2014-06-29	Tentative detection of planet oblateness ( $f = 0.22 \pm 0.11$ ): Kepler-39 b	Zhu et al. (2014b)
2014-07-25	Gemini Planet Imager (GPI) planetary spectroscopy: HR 8799 c and d	Ingraham et al. (2014)
2014-08-04	Hot Jupiter pair in a binary star system: WASP-94A/B	Neveu-VanMalle et al. (2014)
2014-10-20	First planet from the revised Kepler K2 mission: K2-1 (WASP-28, HIP 116454)	Vanderburg et al. (2015b)
2014-10-23	Simultaneous ground-Spitzer parallax and lens mass: OGLE-2014-BLG-124L	Udalski et al. (2015b)
2014-11-28	Hot-Jupiter with an extremely grazing transit: Kepler-447 b	Lillo-Box et al. (2015)
2015-01-26	Jupiter twin around a solar twin: HIP 11915	Bedell et al. (2015)
2015-03-03	Earth-like ( $1.6R_{\oplus}$ ) planet in habitable zone of a Sun-like (G2) star: Kepler-452	Jenkins et al. (2015)
2015-06-11	Minor bodies transiting a polluted white dwarf: WD 1145+017	Vanderburg et al. (2015a)
2015-09-11	Star showing irregular aperiodic flux dips with durations 5–80 d: KIC-8462852	Boyajian et al. (2016)
2015-09-23	Rotational modulation from surface imaging with HST-WFC3: 2M J1207 b	Zhou et al. (2016d)
2015-10-14	Winds on opposing limbs imply first spatial-resolution of an exoplanet: HD 189733 b	Louden & Wheatley (2015)
2015-11-23	First transiting planet in the Hyades cluster: K2-25	Mann et al. (2016a)
2016-01-11	Transiting Jupiter analogue: Kepler-167 e ( $R_{\text{p}} = 0.9R_{\text{J}}$ , $e = 0.06$ , $P = 2.9$ yr)	Kipping et al. (2016)
2016-04-25	First circumbinary microlensing event: OGLE-2007-BLG-349L(AB)	Bennett et al. (2016)
2016-05-06	Terrestrial-mass planet orbiting Sun's nearest stellar neighbour: Proxima Cen	Anglada-Escudé et al. (2016a)
2016-06-16	Variability in a hot Jupiter's atmosphere: HAT-P-7	Armstrong et al. (2016a)
2016-11-21	Seven terrestrial planets around a nearby ultracool dwarf star, TRAPPIST-1	Gillon et al. (2017c)
2017-09-19	Eighth planet discovered in a transiting system: Kepler-90	Shallue & Vanderburg (2018)
2017-11-01	Discovery of the first interstellar 'vagabond': 1I/2017 U1 ('Oumuamua)	Meech et al. (2017)
2017-12-04	Neptune-mass free-floating planet from microlensing: OGLE-2016-BLG-1540	Mróz et al. (2018)



Table 1.3: Statistics of confirmed exoplanets with constraints on planet radius (from transit measurements) and planet mass (from various dynamical considerations), taking no account of associated accuracies. Numbers are from the NASA Exoplanet Archive, as of 2017 December 31.

Exoplanet mass and radius:	
planets with radius, $R_p$ (distribution given below)	2808
planets with mass, $M_p$ (distribution given below)	706
planets with $M_p \sin i$	652
Counts by radius, $R_p$ :	
$\leq 1.25 R_\oplus$	373
1.25 – $2 R_\oplus$	766
2 – $6 R_\oplus$	1187
6 – $15 R_\oplus$	361
$> 15 R_\oplus$	121
Counts by mass, $M_p$ :	
$\leq 3 M_\oplus$	24
3 – $10 M_\oplus$	90
10 – $30 M_\oplus$	63
30 – $100 M_\oplus$	68
100 – $300 M_\oplus$	167
$> 300 M_\oplus$	294

**Hot Jupiters** The subset of *hot Jupiters*, or short period gas giants, are loosely defined as Jupiter-mass planets with  $a \leq 0.1$  au, or  $P = 3 - 9$  d (e.g. Gaudi et al., 2005), and thus significantly heated by stellar irradiation. Their location in the mass–period diagram for confirmed planets with determined masses is shown in Figure 1.6.

*Very hot Jupiters* have been defined as gas giants with  $P \leq 3$  d (Gaudi et al., 2005; Lo Curto et al., 2006; Beatty & Gaudi, 2008), or  $a \leq 0.025$  au (Ragozzine & Wolf, 2009).

Reference has also been made to *ultra-short-period hot Jupiters*, with  $P < 1$  d, which occur only around stars of  $M_\star \leq 1.25 M_\odot$ . Five were identified in the Galactic bulge by Sahu et al. (2006). Others include WASP–18 b, WASP–19 b, WASP–43 b and WASP–103 b.

*Warm Jupiters* are loosely classed as those with  $a \sim 0.1 - 1$  au ( $P \geq 10$  d), and pose similar challenges to understanding their formation pathway(s) (§10.10.6).

**Occurrence** Despite their importance in radial velocity and transit surveys, the occurrence of hot Jupiters around solar-type stars is rather low (TriAUD et al., 2013a). It has been estimated as  $1.5 \pm 0.6\%$  from radial velocity surveys (Cumming et al., 2008), but as low as  $0.5 \pm 0.1\%$  from Kepler (Howard et al., 2012b). Statistics are complicated by stellar multiplicity, evolutionary state, and metallicity (Wang et al., 2015c; Guo et al., 2017a). Debate about their occurrence around M dwarfs continues (e.g. Johnson et al., 2010d, 2012b; Bonfils et al., 2013a; Obermeier et al., 2016b), of relevance to gas giant formation as a function of disk mass (e.g. Laughlin et al., 2004a; Ida & Lin, 2005b; Alibert et al., 2011; Mordasini et al., 2012a).

Although intrinsically rare, hot Jupiters were prominent amongst early discoveries, and their origin and properties continue to attract strong interest. They are considered further in the sections on their occurrence in radial velocity surveys (§2.11.4), properties from transit observations (§6.28), and current understanding of their formation (§10.7.1).

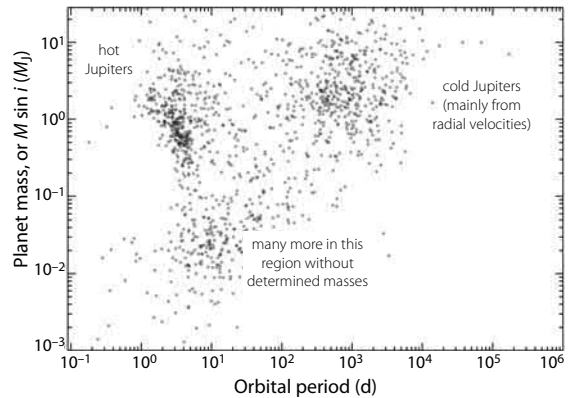


Figure 1.6: The location of hot Jupiters in the mass–orbital period diagram. Only objects with mass determinations provided in the NASA Exoplanet Archive are indicated (as of the end of 2017), therefore omitting many other confirmed planets, especially in the lower left region of the diagram where, for most of the transiting planets, only radii are more directly available (cf. Table 1.3). Although objects from all discovery methods are included, the plot is dominated by radial velocity and transit discoveries. Darker points only delineate overlapping symbols.

### 1.6.3 Earths and super-Earths

**Super-Earths** As noted above, super-Earth planets are loosely classified as those of mass  $2 - 10 M_\oplus$ . The first discoveries with  $M \leq 10 M_\oplus$  began with GJ 876 d, a Doppler-detected  $7.5 M_\oplus$  planet at 0.02 au (Rivera et al., 2005), OGLE–2005–BLG–390L b, a microlensed  $5 M_\oplus$  planet at 5 au (Beaulieu et al., 2006), and HD 69830 b, a Doppler-detected  $10.8 M_\oplus$  planet at 0.08 au (Lovis et al., 2006).

Other notable early discoveries include CoRoT–7 b (Léger et al., 2009) and GJ 1214 b (Charbonneau et al., 2009). Their bulk composition cannot be uniquely determined from their mass and radius alone, and many have average densities consistent with a broad range of bulk compositions, including both H<sub>2</sub>O-dominated, and rocky planets covered by a thick H/He atmosphere. Resolving these degeneracies requires constraints on the planet’s atmospheric structure and composition.

Kepler has shown that super-Earths are amongst the most common planet type around nearby Sun-like stars. There is no direct solar system analogue and, in terms of formation, they remain poorly understood (§10.7.3).

Two particular classes of Earths/super-Earths which are presumed to exist, and which have received specific attention, are the so-called ‘lava planets’, with a surface mostly or entirely covered by molten lava (§11.3.7), and the ‘ocean planets’, formed beyond the snow line with a significant mass fraction in H<sub>2</sub>O (§11.3.8).

**Earth-mass planets** Planets of order one to a few  $M_\oplus$ , variously classified as ‘terrestrial’, ‘telluric’, or ‘rocky’ (both ‘terrestrial’ from Terra, and ‘telluric’ from Tellus are from the Latin for Earth) are considered to be composed primarily of silicate rocks or metals, i.e. Earth-

Table 1.4: A selection of on-line catalogues, associated data, and software tools, of particular relevance to exoplanet research.

URL	Content	Comment
Exoplanet catalogues and related:		
exoplanetarchive.ipac.caltech.edu	NASA Exoplanet Archive	Exoplanet archive, transit data, and statistics
exoplanet.eu	Extrasolar Planets Encyclopaedia	Catalogue and bibliography (all methods)
exoplanets.org	Exoplanet Orbit Database	Critical compilation of exoplanet orbits
univie.ac.at/adg/schwarz/multiple.html	Exoplanets in binary systems	Compilation of star and planet data
microlensing-source.org	Microlensing source	Various resources on all aspects of microlensing
phl.upr.edu/hec	Planetary Habitability Laboratory	Compilation of habitable candidates
www.hzgallery.org	Habitable Zone Gallery	Habitable zone information
Transit data:		
kepler.nasa.gov	Kepler mission	Kepler (and SuperWASP) planets/candidates
idoc-corot.ias.u-psud.fr	CoRoT mission	CoRoT (and MOST) data archive
var.astro.cz/etd	Exoplanet transit database	Compilation of exoplanet transits
www.astro.keele.ac.uk/jkt/tepcat	Transiting planet properties	Compilation, including Rossiter–McLaughlin effect
Related catalogues and compilations:		
exoplanetarchive.ipac.caltech.edu/docs/occurrence_rate_papers.html	Planet occurrence rates	Compilation of papers on occurrence rates
astro.up.pt/resources/sweet-cat	Stellar parameters	Catalogue (SWEET-Cat) of $T_{\text{eff}}$ , $\log g$ , [Fe/H] etc.
minorplanetcenter.org/iau/lists/MPLists.html	Solar system minor planets	By category: PHAs, TNOs, Centaurs, etc
web.gps.caltech.edu/mbrown	Solar system dwarf planets	Confirmed and candidate dwarf planets
www.passc.net/EarthImpactDatabase	Earth Impact Database	Known impact cratering events on Earth
meteoriticalsociety.org	Meteoritical Bulletin Database	Listing of meteorites that have been found on Earth
www.atnf.csiro.au/research/pulsar	ATNF pulsar catalogue	Detailed characteristics of all known radio pulsars
www.exomol.com	ExoMol Database	Molecular line lists for exoplanet atmospheres
Selected astronomy resources:		
adsabs.harvard.edu...and...esoads.eso.org	SAO–NASA ADS	Bibliographic data portal, including arXiv
simbad.u-strasbg.fr	CDS SIMBAD	Comprehensive astronomy object database
cdsweb.u-strasbg.fr/cgi-bin/Dic	IAU Commission 5 WG	Dictionary of nomenclature of celestial objects
planetarynames.wr.usgs.gov	Names of planets/satellite/rings	IAU WG for Planetary System Nomenclature
Software tools:		
ascl.net	Astrophysics Source Code Library	Compilation of astronomy software, listed in ADS
idlastro.gsfc.nasa.gov	NASA–GSFC IDL repository	Codes in IDL as deposited by providers
keplerscience.arc.nasa.gov/software.html	Kepler/K2 software tools	Mostly software specific to Kepler/K2

like in terms of composition. Within the solar system, the terrestrial planets are the four closest to the Sun, i.e. Mercury, Venus, Earth, and Mars (Section 12.2.1).

Unlike the larger giant planets, terrestrial planets have a solid surface, and may have the same basic type of structure, comprising a central metallic core, mostly iron, with a surrounding silicate mantle, and with typical densities around  $5\text{--}8\text{ Mg m}^{-3}$ . Terrestrial planets are considered to have secondary atmospheres, generated through outgassing or comet impacts, in contrast to the giant planets, whose atmospheres are primary, captured directly from the original solar nebula (§11).

Examples include the two Earth-sized planets ( $0.87$  and  $1.03R_{\oplus}$ ) of Kepler–20 (Fressin et al., 2012b); two ( $0.76$  and  $0.87R_{\oplus}$ ) in the Kepler–70 system (Charpinet et al., 2011; Bear & Soker, 2012); and three ( $0.78$ ,  $0.73$ , and  $0.57R_{\oplus}$ ) orbiting Kepler–42 (Muirhead et al., 2012b).

## 1.7 On-line reference compilations

In general, references to on-line compilations or resources, or institute or instrument www pages, have been avoided because of changing URLs, or the frequent absence of long-term maintenance. Certain www sites, nevertheless, are repositories of up-to-date information, and a selection of some of the most relevant are listed in Table 1.4. Amongst these:

**NASA Exoplanet Archive** The online NASA Exoplanet Archive (Akeson et al., 2013) hosts an extensive repository of data related to all confirmed exoplanets (as well as Kepler *candidates*). Accessible via searchable tabular compilations, or host star and planet overviews, data include comprehensive information on the host star (including mass, radius, distance, magnitudes, etc.), as well as on each planet (including mass, radius, orbital data, discovery references, and many other details and flags). It includes light curves from the Kepler and CoRoT missions and from several ground-based surveys, and spectra and radial velocity measurements from the literature.

**Extrasolar Planets Encyclopedia** This independent online database for extrasolar planetary-mass candidates contains updated and extensive information about planets, host stars, and the associated literature, along with online tools for constructing various histograms and cross-correlations (Schneider et al., 2011).

**Exoplanet Orbit Database** The Exoplanet Orbit Database compiles orbital, transit, host star, and other parameters of confirmed exoplanets with ‘good orbits’, listing 2925 as of the end of 2017 (along with other confirmed planets with lower quality orbits). The database can be navigated through the Exoplanet Data Explorer plotter and table (Wright et al., 2011b; Han et al., 2014).

Table 1.5: Some other record holders or (selective) numbers of interest.

Exoplanets:	
Highest precision on ground-based transit photometry: 16 Cyg A (§6.11.4)	60 ppm (over 30 min)
Highest precision on mid-transit time: TrES-2 b (§6.11.6)	$\tau_{\text{mid}} = 0.3 \text{ s}$
Highest precision on orbital period (other than pulsars): WASP-19	$P = 0.788838989 \pm 0.00000004 \text{ d}$ (0.03 s)
Largest transit timing variations: Kepler-90 g (§6.20.6)	$\delta t = 25.7 \text{ h}$
Lowest density planets: Kepler-51 b,c,d (Masuda, 2014)	$\rho \sim 0.03 - 0.04 \text{ Mg m}^{-3}$
Highest density planets: CoRoT-3 b, KELT-1 b	$\rho \sim 25 \text{ Mg m}^{-3}$
Largest radius transiting planet: WASP-79	$R_p = 2.09 R_j$
Most precise planet radius: Kepler-444 b (Mills & Fabrycky, 2017b)	$R_p = 0.406 \pm 0.013 R_{\oplus}$ ( $\pm 80 \text{ km}$ )
Hottest (irradiated) planet: KELT-9 b	$T_{\text{eq}} = 4050 \text{ K}$
Largest tide raised on a planet: WASP-19 b (§10.11.2)	$\epsilon \sim 6 \times 10^{-2} \sim 0.9 R_{\oplus}$
Largest angular size of stellar disk subtended at planet surface: WASP-12	$\Delta \theta \sim 35^\circ$
Highest multi-planet mean motion resonance chain: K2-138 b-c-d-e-f	5 planets in a 3:2 resonance chain
Temperature decrement of tidally-induced (stellar) gravity darkening: HAT-P-7	$\Delta T = -0.18 \text{ K}$
Highest precision on stellar obliquity: WASP-33 (§6.18)	$\lambda = -112.93^{+0.23}_{-0.22} \text{ deg}$
Youngest host stars: DH Tau, GQ Lup, etc. (imaging); V830 Tau (radial velocity)	1-2 Myr
Oldest host stars: HAT-P-18, HAT-P-22, etc.	12.4 Gyr
Oldest star harbouring a rocky planet: Kepler-10	$10.41 \pm 1.36 \text{ Gyr}$
Lowest metallicity host star (radial velocity): BD+20 2457	[Fe/H] = -1.00 dex
Lowest metallicity host star (transit): Kepler-271	[Fe/H] = -0.95 dex
Highest metallicity host star (radial velocity): HD 47536	[Fe/H] = +0.69 dex
Highest metallicity host star (transit): Kepler-378	[Fe/H] = +0.55 dex
Roundest object in Nature: KIC-11145123 (box, page 216)	$\Delta R/R = (1.8 \pm 0.6) \times 10^{-6}$
Solar system:	
Sun's age (§12.1.4)	$4.57 \pm 0.11 \text{ Gyr}$
Oldest minerals on Earth (§12.1.4)	4.404 Gyr
Cooling rate of Earth's interior (box, page 663)	$\sim 0.1 \text{ K Myr}^{-1}$
Earth's solid core radius increase (box, page 663)	$\sim 0.5 - 1.0 \text{ mm yr}^{-1}$
Most rapid geomagnetic reversal on Earth, Laschamp, at 41 ka (box, page 663)	$\Delta t \sim 440 \text{ yr}$
Largest tidal amplitude: Jupiter, due to Io (§10.11.2)	$c \sim 2 \times 10^{-7}$
Cooling rate of Jupiter (§11.3.3)	$\Delta T_{\text{eff}} = -6.9 \text{ K Gyr}^{-1}$
Closest past stellar encounter, WISE J0720 (§12.1.6)	$0.25 \pm 0.1 \text{ pc}$ , at 70 ka
Dates for observers:	
Next planet-planet transit in the Kepler-89 system, planets d and e (§6.14.16)	2026 April 1/2
Re-commencement of transits in the Kepler-16 circumbinary system (§6.31)	2042
Next simultaneous transit of Mercury and Venus visible from Earth (box, page 227)	69 163 July 26

## 1.8 Future developments

Future advances in radial velocity measurements from the ground are anticipated with VLT-ESPRESSO (§2.6.6), which saw first light in 2017 November, and E-ELT-HIRES (§2.6.6), targeted in 2024.

Expected advances from space instrumentation include the significant improvements in distances, space motions and, eventually, planet discoveries expected from Gaia (§3.9), with DR2 released in 2018 April.

Substantial advances are expected in transit studies with TESS (§6.8.1, launched 2018 April 18), CHEOPS (§6.8.3, launch scheduled for late 2018), JWST (§6.8.3, launch scheduled for 2020), and PLATO (§6.8.1, launch scheduled for 2026).

Significant advances are expected in microlensing (and transits) with Euclid and WFIRST-AFTA (§5.9.5), with launches foreseen in the period 2020-25.

Table 1.6: Extreme transiting and radial velocity systems. Source: NASA Exoplanet Archive, 2017 December 31.

Transiting		Radial velocity	
<i>Brightest hosts:</i>	<i>V (mag)</i>	<i>Brightest hosts:</i>	<i>V (mag)</i>
KELT-9	7.6	$\alpha$ Tau	0.8
KELT-20	7.6	HD 62509 ( $\beta$ Gem)	1.1
KELT-11	8.0	$\gamma^1$ Leo	1.9
WASP-33	8.1	$\alpha$ Ari	2.0
Kepler-21	8.3	$\beta$ UMi	2.1
<i>Nearest systems:</i>	<i>d (pc)</i>	<i>Nearest systems:</i>	<i>d (pc)</i>
GJ 1132	12.0	Proxima Cen	1.3
TRAPPIST-1	12.1	$\epsilon$ Eri	3.2
LHS 1140	12.5	Ross 128	3.4
GJ 1214	13.0	GJ 15A	3.6
K2-135	30.3	YZ Cet	3.6
<i>Shortest period:</i>	<i>P (d)</i>	<i>Shortest period:</i>	<i>P (d)</i>
K2-137	0.18	55 Cnc e	0.74
Kepler-78 b	0.35	GJ 3138 b	1.22
K2-131	0.37	HD 41004B b	1.33
K2-22 b	0.38	GJ 876 d	1.94
Kepler-42 c	0.45	YZ Cet b	1.97
<i>Longest period:</i>	<i>P (d)</i>	<i>Longest period:</i>	<i>P (d)</i>
WASP-53 c	2840	HIP 70849 b	17337
KIC 3558849 b	1322	47 UMa d	14002
KIC 5951458 b	1320	HD 30177 c	11613
Kepler-1647 b	1108	HIP 5158 c	9018
Kepler-167 e	1071	GJ 676A c	7337
<i>Smallest radius:</i>	<i>R<sub>p</sub> (R<sub>J</sub>)</i>	<i>Smallest mass:</i>	<i>M<sub>p</sub> sin i (M<sub>J</sub>)</i>
Kepler-37 b	0.029	YZ Cet b-d (all 3)	0.003
Kepler-444 b	0.036	GJ 273 c	0.004
Kepler-102 b	0.042	Proxima Cen b	0.004
Kepler-444 c	0.044	Ross 128 b	0.004
Kepler-1308 b	0.046	GJ 581 e	0.005
<i>Largest eccentricity:</i>	<i>e</i>	<i>Largest eccentricity:</i>	<i>e</i>
WASP-53 c	0.84	HD 20782 b	0.96
Kepler-419 b	0.83	HD 80606 b	0.93
Kepler-420 b	0.77	HD 4113 b	0.90
Kepler-75 b	0.57	HD 76920 b	0.86
CoRoT-20 b	0.56	HD 108341 b	0.85
<i>Highest multiplicity:</i>	<i>n (p)</i>	<i>Highest multiplicity:</i>	<i>n (p)</i>
Kepler-90	8	HD 10180	6
TRAPPIST-1	7	HD 34445	6
Kepler-11, Kepler-20, Kepler-80	6	HD 219134	6
HIP 41378, Kepler-102, and others	5	GJ 667C, HD 40307, and 55 Cnc	5

# Radial velocities

THE MOTION OF A SINGLE PLANET in orbit around a star causes the star to undergo a reflex motion about the star–planet *barycentre* (centre of mass). This results in the periodic perturbation of three observable properties of the star, all of which have been detected (albeit typically in different systems): in radial velocity, in angular (or astrometric) position on the sky (Chapter 3), and in the time of arrival of some periodic reference signal (Chapter 4).

The first convincing exoplanet detection was made by radial velocity measurements in 1995. By the end of 2017, 662 planets in 504 systems (102 of which are multiple) have been discovered by this technique, with a dozen or so which also transit their host star.

## 2.1 Orbits and orbit fitting

### 2.1.1 Description of orbits

As in all orbiting systems, both star and planet orbit the common system barycentre. Under the inverse square law of gravity<sup>1</sup>, each moves in a closed elliptical orbit in inertial space, with the centre of mass at one focus (Figure 2.1). Such an ellipse is described in polar coordinates (with respect to a focus) by

$$r = \frac{a(1 - e^2)}{1 + e \cos \nu}, \quad (2.1)$$

or in Cartesian coordinates (with respect to the centre)

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1, \quad (2.2)$$

with the semi-major axis  $a$  and the semi-minor axis  $b$  related to the *eccentricity*  $e$  by

$$b^2 = a^2(1 - e^2). \quad (2.3)$$

<sup>1</sup>The relations given in this section, their derivations, and more extensive dynamical considerations, can be found in various recent texts (e.g., Murray & Dermott 2000, Chapter 2; Hilditch 2001; Cole & Woolfson 2002, Section M) as well as in a number of earlier authoritative treatments of orbits (e.g. Aitken, 1918; Binnendijk, 1960; Batten, 1973; Heintz, 1978a; Roy, 1978).

[The *ellipticity*,  $\eta = (a - b)/a = 1 - \sqrt{1 - e^2}$ , is an alternative measure of non-circularity, not used further.]

The *pericentre* distance  $q$  and *apocentre* distance  $Q$  are given by<sup>2</sup>

$$\begin{aligned} q &= a(1 - e), \\ Q &= a(1 + e). \end{aligned} \quad (2.4)$$

A line through a focus and parallel to the minor axis defines the *latus rectum*, with the *semi-latus rectum* (related to the planet's angular momentum) of length

$$p = a(1 - e^2). \quad (2.5)$$

**True, eccentric, and mean anomaly** Various angles in the orbit plane, referred to as ‘anomalies’ (the word dating from the time that planetary motions were considered anomalous), are used to describe the position of a planet along its orbit at a particular time (Figure 2.1).

The *true anomaly*,  $\nu(t)$ , also frequently denoted  $f(t)$ , is the angle between the direction of pericentre and the current position of the body measured from the barycentric focus of the ellipse. It is the angle normally used to characterise an observational orbit.

The *eccentric anomaly*,  $E(t)$ , is a corresponding angle which is referred to the *auxiliary circle* of the ellipse. The true and eccentric anomalies are geometrically related by

$$\cos \nu(t) = \frac{\cos E(t) - e}{1 - e \cos E(t)}, \quad (2.6)$$

or, equivalently,

$$\tan \frac{\nu(t)}{2} = \left( \frac{1 + e}{1 - e} \right)^{1/2} \tan \frac{E(t)}{2}. \quad (2.7)$$

<sup>2</sup>An *apsis* (plural *apsides*) is the point on the orbit of minimum distance (*pericentre*, or *periapsis*) or maximum distance (*apocentre*, or *apoapsis*) from the barycentre. The line connecting the two is the *line of apsides*, which defines the orbit's major axis. Derivative terms refer to the body being orbited: perigee/apogee around the Earth, perihelion/aphelion around the Sun, periastron/apastron around a star, peribac/apobac around a barycentre, and perigalacticon/apogalacticon around a galaxy. The general terms pericentre/apocentre are used preferentially here.

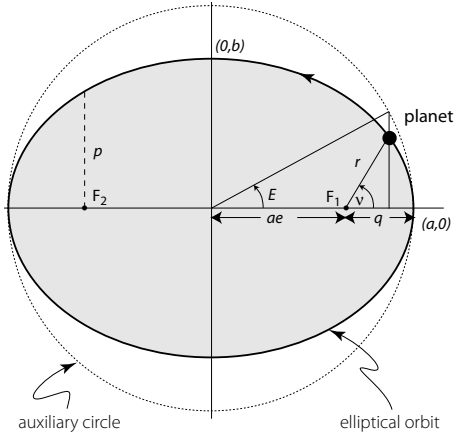


Figure 2.1: Geometry of an elliptical orbit. Points on the orbit can be described in terms of the true anomaly  $v$  (with respect to the ellipse) or the eccentric anomaly  $E$  (with respect to an auxiliary circle of radius equal to the semi-major axis  $a$ ). Focus  $F_1$  is the system barycentre,  $F_2$  is the ‘empty’ focus.

The *mean anomaly*,  $M(t)$ , is an angle related to a fictitious mean motion around the orbit, used in calculating the true anomaly. Over a complete orbit, during which the real planet (or the real star) does not move at a constant angular rate, an average angular rate can nevertheless be specified in terms of the *mean motion*

$$n \equiv 2\pi / P, \quad (2.8)$$

where  $P$  is the orbital period. The mean anomaly at time  $t - t_p$  after pericentre passage is then defined as

$$M(t) = \frac{2\pi}{P}(t - t_p) \equiv n(t - t_p). \quad (2.9)$$

The relation between the mean anomaly,  $M(t)$ , and the eccentric anomaly,  $E(t)$ , can be derived from orbital dynamics. This relation, *Kepler’s equation*, is given by

$$M(t) = E(t) - e \sin E(t). \quad (2.10)$$

The position of an object along its orbit at any time can then be obtained by calculating the mean anomaly  $M$  at that time from Equation 2.9, (iteratively) solving the transcendental Equation 2.10 for  $E$ , and then using the geometrical identity Equation 2.6 to obtain  $v$ .

An analytical approach, which yields partial derivatives which can be used in various fitting and data analysis methods (including Fisher analysis of co-variances, uncertainties and correlations) is given by Pál (2009).

**Orbit specification** A Keplerian orbit in three dimensions (Figure 2.2) is described by seven parameters:  $a, e, P, t_p, i, \Omega, \omega$ . The first two,  $a$  and  $e$ , specify the size and shape of the elliptical orbit.  $P$  is related to  $a$  and the component masses through Kepler’s third law (see below), while  $t_p$  corresponds to the position of the object

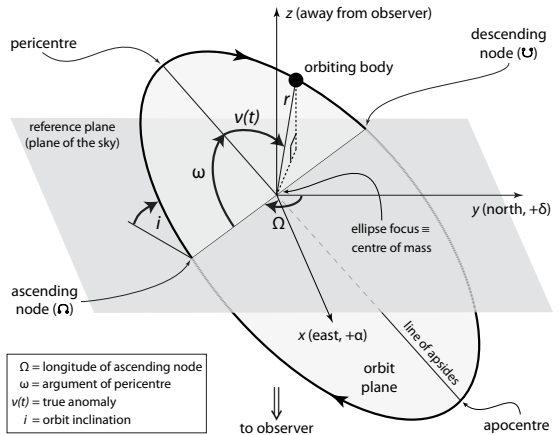


Figure 2.2: An elliptical orbit in three dimensions. The reference plane is tangent to the celestial sphere,  $i$  is the inclination of the orbit plane, and the nodes define the intersection of the orbit and reference planes.  $\Omega$  is the longitude of the ascending (receding) node, measured in the reference plane.  $\omega$  is the fixed angle defining the object’s argument of pericentre relative to the ascending node. The true anomaly,  $v(t)$ , is the time-dependent angle characterising the object’s position along the orbit. The right-handed  $xyz$  coordinate system has  $x$  towards east (increasing  $\alpha$ ),  $y$  towards north (increasing  $\delta$ ), and  $z$  away from the observer, consistent with the Thiele–Innes constants (Equations 3.18–3.20). The reference axis,  $y$ , contrasts with the use of  $x$ , the vernal equinox, as adopted for the solar system.

along its orbit at a particular reference time, generally with respect to a specified pericentre passage.<sup>3</sup>

The three angles ( $i, \Omega, \omega$ ) represent the projection of the true orbit into the observed (apparent) orbit; they depend solely on the orientation of the observer with respect to the orbit. With reference to Figure 2.2:

- $i$  specifies the *orbit inclination* with respect to the reference plane,  $0 \leq i < 180^\circ$ .  $i = 0^\circ$  corresponds to a face-on orbit. For binary star orbits, motion is referred to as prograde (in the direction of increasing position angle on the sky, irrespective of the relation between the rotation and orbit vectors) if  $i < 90^\circ$ , retrograde if  $i > 90^\circ$ , and projected onto the line of nodes if  $i = 90^\circ$ .
- $\Omega$  specifies the *longitude of the ascending node*, mea-

<sup>3</sup>A few remarks are in order: (i) some texts state that just six parameters are required, and omit  $P$ , implicitly invoking the relation between  $a$  and  $P$  (and the component masses) as given by Kepler’s third law; (ii)  $a$  is the semi-major axis of the orbiting body with respect to the system barycentre, assumed here to be in linear measure unless otherwise noted. If  $a$  is determined in angular measure, as in the relative astrometry of binary stars, the system distance  $d$  (equivalently the parallax  $\varpi$ ) is required to establish the linear scale; (iii) the parameters of the two co-orbiting bodies (e.g. a star and planet) with respect to the barycentre are identical, with the exception of their  $a$  which differ by a factor  $M_p/M_*$ , and their  $\omega$  which differ by  $180^\circ$ ; (iv) in general, the semi-major axis of the true orbit does not project into the semi-major axis of the apparent orbit.

sured in the reference plane. It is the node where the object moves away from the observer through the plane of reference, i.e. where  $z$  goes from negative to positive. [For solar system objects, it is the node where an orbiting object moves north through the plane of reference.]

- $\omega$  specifies the *argument of pericentre*. It is the angular coordinate of the object's pericentre relative to its ascending node, measured in the orbital plane and in the direction of motion. [For  $e = 0$ , where pericentre is undefined,  $\omega = 0$  can be chosen such that  $t_p$  gives the time of nodal passage.]

Three other angles with respect to the adopted reference direction are used in the specification of orbits:

$$\tilde{\omega} = \Omega + \omega \quad \text{the longitude of pericentre} \quad (2.11)$$

$$\theta = \tilde{\omega} + \nu \quad \text{the true longitude} \quad (2.12)$$

$$\lambda = \tilde{\omega} + M \quad \text{the mean longitude} \quad (2.13)$$

Since  $\Omega$  and  $\omega$  are measured in different planes, the longitude of pericentre,  $\tilde{\omega}$ , is a 'dog-leg' angle. The true longitude and mean longitude are correspondingly offset with respect to the true anomaly and mean anomaly, respectively. Despite its name, the mean longitude is again a linear function of time and, as for the mean anomaly, has only an auxiliary geometrical interpretation.<sup>4</sup>

**Kepler's laws** Kepler's three laws of planetary motion are: (1) the orbit of a planet is an ellipse with the Sun at one focus; (2) the line joining a planet and the Sun sweeps out equal areas in equal intervals of time; (3) the squares of the orbital periods of the planets are proportional to the cubes of their semi-major axes.

The first and third laws are consequences of the inverse square law of gravity, while the second follows from conservation of angular momentum (and is true for any radial law of attraction). Kepler's laws originally

<sup>4</sup> Various forms of Figure 2.2 are given in the literature. Indeed, this version differs from that in the first edition which, following Batten (1973), erroneously showed  $\Omega$  measured in the direction north through west. With reference to the following standard texts (Lennart Lindegren, priv. comm.): Aitken (1918) provided no figure, but his text is consistent with Figure 2.2. Binnendijk (1960), Figure 25, is drawn for negative  $i$ , i.e. with  $\Omega$  showing the position angle of the *descending* rather than the *ascending* node, following the convention in visual binary work of choosing the node that gives  $\Omega < 180^\circ$ , and indicating the nodal ambiguity by assigning  $i = \pm X^\circ$  (with  $X > 90^\circ$  for a retrograde orbit). The positive sign would then mean that the node is ascending, negative that it is descending. If the ambiguity is subsequently resolved by radial velocity data, and it turned out that  $\Omega$  referred to the descending node, one could either (1) retain  $\Omega$  and assign  $i < 0^\circ$ , or (2) increase  $\Omega$  by  $180^\circ$ , increase  $\omega$  by  $180^\circ$ , and assign  $i > 0^\circ$  (and so preserving the 6 Thiele–Innes constants, §3.4.5). Batten (1973), Figure 1.3, erroneously shows  $\Omega$  drawn from north through west, whereas it should be measured from north through east, as stated in his text (pp 9–10). Heintz (1978a), Figure 7, is wrong in the same way as Batten (1973).

referred to relative orbits with respect to the Sun, but corresponding formulations apply also to 'absolute orbits' defined with respect to the barycentre.

For the general two-body problem where the mass of the secondary is not neglected, both orbits are ellipses with their foci at their common barycentre (Figure 2.3). Kepler's third law takes the general form

$$P^2 = \frac{4\pi^2}{GM} a^3, \quad (2.14)$$

with  $M$  and  $a$  taking different values according to the type of orbit being measured:

(a) relative orbits: the motion of the planet, now relative to the star rather than the barycentre (Figure 2.3), can be found by applying an acceleration to the system which cancels that of the star, viz.  $GM_p/r^2$  where  $r$  is the instantaneous star–planet separation

$$r = \frac{a(1 - e^2)}{1 + e \cos \nu}. \quad (2.15)$$

Then

$$P^2 = \frac{4\pi^2}{G(M_\star + M_p)} a_{\text{rel}}^3, \quad (2.16)$$

where the coordinate origin is now the star, not the barycentre, and  $a_{\text{rel}}$  is the semi-major axis of the relative orbit, i.e. of the planet around the star.<sup>5</sup>

For  $M_p \ll M_\star$  and in units of Earth's orbit of 1 au

$$P \approx 1 \text{ yr} \left( \frac{a_{\text{rel}}}{\text{au}} \right)^{3/2} \left( \frac{M_\star}{M_\odot} \right)^{-1/2}. \quad (2.17)$$

(b) absolute orbits: the orbit of the star around the system (star–planet) barycentre is given by

$$P^2 = \frac{4\pi^2}{GM'} a_\star^3, \quad (2.18)$$

where

$$M' \equiv \frac{M_p^3}{(M_\star + M_p)^2}, \quad (2.19)$$

and  $a_\star$  is the semi-major axis of the stellar orbit around the system barycentre. An equivalent expression gives the orbit of the planet around the system barycentre in

<sup>5</sup>This measurement of *relative* separation does not arise for exoplanet orbits when the planet is unseen. It is, in contrast, a situation relevant for the relative astrometry of binary stars, where an orbit is measured as a separation and position angle of one star with respect to another; then, the combined system mass can be determined if  $P$  and  $a_{\text{rel}}$  are measurable, while individual masses can only be determined if the mass ratio can be established, either from the ratio of the distances from the barycentre, or the ratio of their speeds around it.

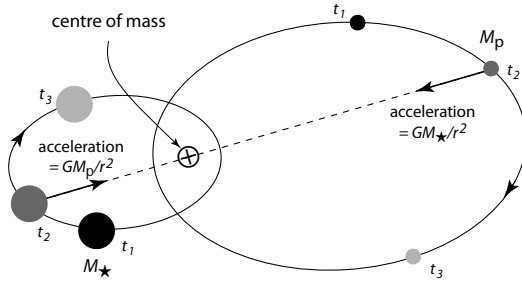


Figure 2.3: Two orbiting bodies, shown at times  $t_1, t_2, t_3$ , move about their common barycentre. Both bodies follow orbits having the same shape and period, but of different sizes and with  $\omega$  differing by  $180^\circ$ .

terms of the semi-major axis of the planet around the system barycentre  $a_p$ .

It follows that the sizes of the three orbits are in proportion  $a_* : a_p : a_{\text{rel}} = M_p : M_* : (M_* + M_p)$ , with  $a_{\text{rel}} = a_* + a_p$ . Furthermore,  $e_{\text{rel}} = e_* = e_p$ ,  $P_{\text{rel}} = P_* = P_p$ , the three orbits are co-planar, and the orientations of the two barycentric orbits ( $\omega$ ) differ by  $180^\circ$ .

Since the planet is assumed to be invisible (the case for essentially all radial velocity observations at the present time, although see §2.5.4), the orbital motion of the star around the barycentre is only correctly determined by astrometry if its position is measured with respect to an ‘absolute’ (quasi-inertial) reference frame.

That all seven orbital elements are accessible to astrometric measurements for an arbitrary projection geometry essentially follows from two principal considerations: the star position versus time allows the maximum and minimum angular rates to be determined, and hence the position of the line of apsides. With the orientation of the major axis so established, appeal to Kepler’s second law fixes the orbit inclination.

Radial velocity measurements of the host star also give information on its barycentric orbital motion, although not all seven Keplerian orbital elements are accessible from the line-of-sight velocity variations alone.

### 2.1.2 Orbits from radial velocities

Radial velocity (Doppler) measurements describe the projected motion, along the line-of-sight, of the primary star as it orbits the system barycentre.

**Radial velocity semi-amplitude** With Figure 2.2 now considered as representing the orbit of the star around the barycentre, the star’s  $z$ -coordinate along the line-of-sight can be derived from trigonometry

$$z = r(t) \sin i \sin(\omega + \nu), \quad (2.20)$$

where  $r(t)$  is the distance from the barycentre. Then

$$v_r \equiv \dot{z} = \sin i [\dot{r} \sin(\omega + \nu) + r \dot{\nu} \cos(\omega + \nu)]. \quad (2.21)$$

Some algebraic substitutions for  $r$  and  $\dot{r}$  lead to

$$v_r = K [\cos(\omega + \nu) + e \cos \omega], \quad (2.22)$$

where the *radial velocity semi-amplitude* is given by<sup>6</sup>

$$K \equiv \frac{2\pi}{P} \frac{a_* \sin i}{(1 - e^2)^{1/2}}. \quad (2.23)$$

From Equation 2.22, it can be seen that  $v_r$  varies around the orbit between limits of  $K(1 + e \cos \omega)$  and  $K(-1 + e \cos \omega)$ . This expression for  $v_r$  as a function of the true anomaly  $\nu(t)$  can be transformed into an expression for  $v_r$  as a function of time through Equations 2.6–2.10.

The shape of the radial velocity curve is determined by  $e$  and  $\omega$  (Figure 2.4). Together with  $P$ , their combination constrains the value of  $a_* \sin i$  (Equation 2.23). But neither  $a_*$  nor  $\sin i$  can be determined separately.

Two alternative expressions for  $K$  are instructive. Substituting Equations 2.18 and 2.19 into 2.23 gives

$$K^2 = \frac{G}{(1 - e^2)} \frac{1}{a_* \sin i} \frac{M_p^3 \sin^3 i}{(M_* + M_p)^2}. \quad (2.24)$$

With the product  $a_* \sin i$  determined as above, it follows that radial velocity measurements provide a value for the *mass function* (i.e. Equation 2.19 modified by a dependency on the orbit inclination)

$$\mathcal{M} \equiv \frac{M_p^3 \sin^3 i}{(M_* + M_p)^2}. \quad (2.25)$$

For  $M_p \ll M_*$  this reduces to

$$\mathcal{M} \approx \frac{M_p^3 \sin^3 i}{M_*^2}. \quad (2.26)$$

Further, if  $M_*$  can be estimated from its spectral type and luminosity class (or otherwise), then  $M_p \sin i$  can be determined. The mass of the planet nevertheless remains uncertain by the unknown factor  $\sin i$ .

Equations 2.18, 2.19 and 2.23 can be combined to give an alternative expression for  $K$  without the explicit appearance of  $a_*$  (e.g. Cumming et al., 1999, eqn 1)

$$K = \left( \frac{2\pi G}{P} \right)^{1/3} \frac{M_p \sin i}{(M_* + M_p)^{2/3}} \frac{1}{(1 - e^2)^{1/2}}, \quad (2.27)$$

which can also be written (Torres et al., 2008, eqn 1)

$$\frac{M_p \sin i}{M_J} = 4.919 \times 10^{-3} \left( \frac{K}{\text{ms}^{-1}} \right) (1 - e^2)^{1/2} \left( \frac{P}{\text{days}} \right)^{1/3} \left( \frac{M_* + M_p}{M_\odot} \right)^{2/3}. \quad (2.28)$$

<sup>6</sup>Often denoted  $K_1$  in binary star work to emphasise the motion of the primary, this amplitude of radial motion is analogous to the projected semi-major axis measured astrometrically.



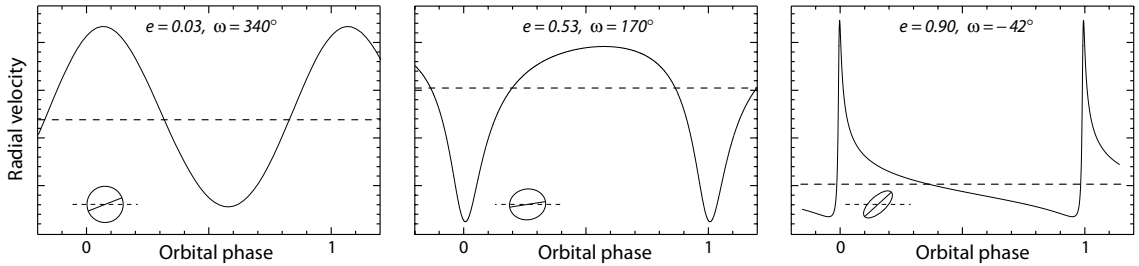


Figure 2.4: Example stellar radial velocity curves, illustrating their dependence on  $e$  and  $\omega$ , for HD 73256 (Udry et al., 2003a, Figure 2), HD 142022 (Eggenberger et al., 2006, Figure 4), and HD 4113 (Tamuz et al., 2008, Figure 1). Horizontal dashed lines show the systemic velocity (viz. the radial velocity of the barycentre). The ellipses at lower left show the viewing geometries.

For a circular orbit with  $M_p \ll M_\star$ , for example, the stellar velocity variations are sinusoidal with amplitude

$$K = 28.4 \text{ m s}^{-1} \left( \frac{P}{1 \text{ yr}} \right)^{-1/3} \left( \frac{M_p \sin i}{M_J} \right) \left( \frac{M_\star}{M_\odot} \right)^{-2/3}. \quad (2.29)$$

For Jupiter around the Sun ( $a = 5.2 \text{ au}$ ,  $P = 11.9 \text{ yr}$ )  $K_J = 12.5 \text{ m s}^{-1}$ . For Earth,  $K_\oplus = 0.09 \text{ m s}^{-1}$ .

**Keplerian observables** Of the 7 elements describing an orbit in three-dimensions ( $a, e, P, t_p, i, \Omega, \omega$ ),  $\Omega$  cannot be determined from radial velocity measurements (cf. Figure 2.2). Furthermore, only the combination  $a_\star \sin i$  is determined, with neither  $a_\star$  nor  $\sin i$  individually.

Radial velocity measurements alone do not provide individual planetary masses, their sum, or their ratio.<sup>7</sup> Taken alone, small periodic radial velocity modulation is insufficient to infer, unambiguously, the presence of a companion of planetary mass. Without additional information, such as an astrometric orbit, a constraint on the orbit inclination  $i$  from photometric transits, spectroscopic line profiles, or statistical deconvolution (e.g. Jorissen et al., 2001), small values of  $K$  could indicate either a low-mass planet, or an object of significantly higher mass with small orbital inclination, i.e. with the plane of the orbit almost face-on to the line-of-sight.

**Periodogram analysis** In single- or multiple-planet fitting, preliminary period estimates are often used to simplify the search, for example using the Lomb–Scargle algorithm (Lomb, 1976; Scargle, 1982). This modified periodogram analysis, equivalent to least-squares fitting of sine waves, targets the efficient and reliable detection of a periodic signal in the case of unevenly-spaced observation times and in the presence of noise.

<sup>7</sup>For double-lined spectroscopic binaries with two distinct spectra (not the case for typical exoplanet orbits, but see §2.5.4), the mass function for each component can be established separately. Then the component mass ratio can also be estimated, but still neither the separate masses, nor the orbit inclination. Further inferences can be made if the system is eclipsing (such that  $i \approx 0$ ), or if the system can also be resolved astrometrically.

Although not generally as robust as Bayesian methods in selecting and quantifying signals (e.g. through MCMC, §2.1.5), they are computationally efficient and are good at signal visualisation (Figure 2.5).

**Variations** Variations of the Lomb–Scargle periodogram have been developed to variously account for measurement errors (e.g. Horne & Baliunas, 1986; Gilliland & Baliunas, 1987; Irwin et al., 1989; Baluev, 2008a; Vio et al., 2013); a frequency-dependent mean (e.g. Cumming et al., 1999; Zechmeister et al., 2009); non-sinusoidal functions (e.g. Bretthorst, 2001; Cumming, 2004); multiple periodic signals (e.g. Anglada-Escudé & Tuomi, 2012; Baluev, 2013a; Jenkins et al., 2014; Hara et al., 2017), Bayesian formalism using marginalised likelihoods caused by stellar activity (Mortier & Collier Cameron, 2017).

Most searches account for white noise through weighting by measurement errors. Algorithms have also been developed to treat correlated ‘red noise’ (e.g. in time or wavelength), such as `RedFit` for paleoclimate data (Schulz & Mudelsee, 2002), and `Agatha` for radial velocities (Feng et al., 2017a).

A comparative evaluation of the the generalised Lomb–Scargle periodogram (GLS), the modified Bayesian formalism (BGLS), and the multifrequency periodogram scheme (FREDEC, for frequency decomposer; Baluev, 2013a) was carried out by Pinamonti et al. (2017). For more complex signals, the residual analyses of GLS and BGLS yielded 30% false alarms, compared to some 10% for FREDEC.

### 2.1.3 Single planet fitting

There are five observables related to the star’s Keplerian orbit which can be estimated for each planet on the basis of radial velocity measurements alone:  $e$ ,  $P$ ,  $t_p$ , and  $\omega$ , and the combination  $K = f(a, e, P, i)$ .

Two further terms are usually taken into account: a *systemic velocity*,  $\gamma$ , describing the constant component of the radial velocity of the system’s centre of mass relative to the solar system barycentre, which may also include an instrument-dependent radial velocity offset; and a linear trend parameter,  $d$ , which may accommodate instrumental drifts as well as unidentified contributions from massive, long-period companions.

From Equation 2.22, the radial velocity of a star with an orbiting planet can then be expressed as a function of

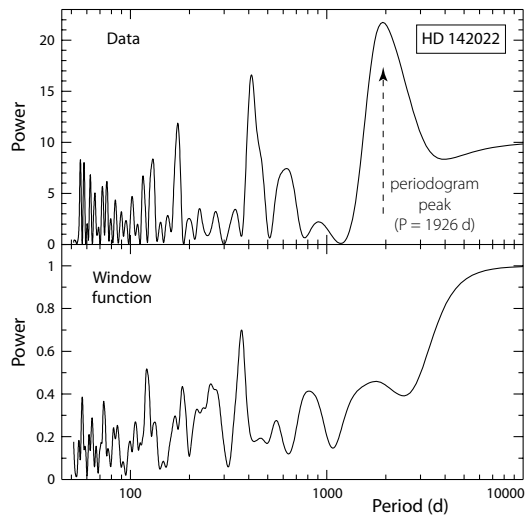


Figure 2.5: Lomb–Scargle periodogram analysis applied to radial velocities for HD 142022 from CORALIE. The power indicates the signal’s statistical significance, not its true amplitude. The window function, determined by the observation epochs, is shown below. The highest peak corresponds to  $P = 1926$  d, while the best-fit solution gives  $P = 1928$  d. From Eggenberger et al. (2006, Figure 2), reproduced with permission © ESO.

the true anomaly as (e.g. Wright & Howard, 2009, eqn 1)

$$v_{\text{r}}(t) = K [\cos(\omega + \nu(t)) + e \cos \omega] + \gamma + d(t - t_0). \quad (2.30)$$

Establishing the astrometric or radial velocity parameters for a single orbiting planet is typically based on the search of parameter space using  $\chi^2$  minimisation.

Zechmeister & Kürster (2009) give an analytic solution for the generalisation to a full sine wave fit, taking account of measurement errors and an offset. They include a specific algorithm to search for the period of the best-fit Keplerian orbit to radial velocity data. Other analytical methods are described by Delisle et al. (2016).

### 2.1.4 Multiple planet fitting

**Kinematic fitting** For a system of  $n_{\text{p}}$  planets, the total radial velocity signal can be approximated as a linear sum over  $n_{\text{p}}$  terms of the form contained in Equation 2.30, giving a total of  $5n_{\text{p}} + 1$  Keplerian parameters to be fit, including  $\gamma$  (and optionally  $d$ ).

This first-order approach to fitting multiple systems considers that the reflex motions of the star caused by each planet are independent, i.e. ignoring the effects of planet–planet gravitational interactions. In this kinematic (or Keplerian) fitting, the dominant planet signal is identified, its Keplerian contribution subtracted from the observational data, and the process repeated until all significant planet signals have been accounted for. A more rigorous multi-planet  $\chi^2$  fit to the original data can then be made using these results as starting values.

Such an approach was adopted for the five-planet fit to the 18 years of Doppler data for 55 Cnc, with weights assigned to account for signal-to-noise, photospheric motions, and instrument errors (Fischer et al., 2008).

**Linearisation** An alternative to least-squares fitting of Keplerian motions to the radial velocity measurements is to seek linear parameters which can be constructed from certain of the orbital elements.

Konacki & Maciejewski (1999) described a harmonic component analysis which they applied to 16 Cyg. This is based on a Fourier expansion of the Keplerian motion in which the harmonic coefficients are functions of all orbital elements. The coefficients, obtained by linear least-squares, are then used as starting estimates for a local minimisation of the non-linear problem.

Wright & Howard (2009) formulated a linearisation which reduces the search space for  $n_{\text{p}}$  planets from the  $5n_{\text{p}} + 1$  Keplerian parameters to  $3n_{\text{p}}$  non-linear variables corresponding to  $(e, P, t_{\text{p}})$  for each planet. In this approach, Equation 2.30, generalised to the case of  $n_{\text{p}}$  planets, is re-cast as (Wright & Howard, 2009, eqn 4–7)

$$v_{\text{r}}(t) = \sum_{j=1}^{n_{\text{p}}} \left[ h_j \cos \nu_j(t) + c_j \sin \nu_j(t) \right] + v_0 + d(t - t_0), \quad (2.31)$$

where, for each planet,

$$h_j = K_j \cos \omega_j, \quad c_j = -K_j \sin \omega_j, \quad v_0 = \gamma + \sum_{j=1}^n K_j e_j \cos \omega_j.$$

The non-linear terms  $(e, P, t_{\text{p}})$  are then searched for algorithmically (e.g. using the Levenberg–Marquardt or Markov Chain Monte Carlo methods), with the linear parameters  $(h, c, v_0)$ , which are transformable back to  $(\omega, K, \gamma)$ , solved for analytically at each search step.

**Compressed sensing techniques** In an extension of the more advanced periodogram-type analyses described above, new techniques from the field of signal processing are also being applied. Exploiting developments in the analysis of sparse signals, often referred to as *compressed sensing* or *compressive sampling*, Hara et al. (2017) detail a technique which circumvents ‘brute-force’ minimisation (cf. Equations 2.30–2.31) and searches for the presence of all planets simultaneously and rapidly, essentially exploiting the *a priori* information that the representation of an exoplanet signal in the Fourier domain is sparse. They demonstrated the method with published radial velocity data for 55 Cnc, GJ 876, HD 10180 and HD 69830.

**Dynamical fitting** In numerous multi-planet systems, gravitational interaction between two or more planets further modifies the total radial velocity or ‘astrometric signature’ as a function of time. Such interaction can result in detectable variations in the planetary orbits even

over short intervals measured in years. A more complete dynamical (or Newtonian) fit involving N-body integrations must then be used.

Various self-consistent algorithms, which incorporate mutual perturbations in fitting the radial velocity data, were developed for the first resonantly interacting system GJ 876, resulting in substantially improved fits to the radial velocity data (Laughlin & Chambers, 2001; Rivera & Lissauer, 2001; Nauenberg, 2002a; Lee & Peale, 2002). The latter was verified against full hydrodynamic evolution of embedded planets by Kley et al. (2004).

Even good dynamical fits can result in orbital parameter solutions which might be stable over years or decades, but unstable on time scales comparable to the age of the planetary system. Since such formal solutions may be considered as implausible, short-term and long-term dynamical stability is a further constraint that must be satisfied by multiple planet orbit fitting. The issue is considered further in §2.12.

**Degeneracies** In inadequately-sampled data, model ambiguities can frequently arise (e.g. Morais & Correia, 2011). Ambiguities between high eccentricity and multiple planet fits can also arise from various degeneracies (Wittenmyer et al., 2013c): (a) between a single planet on an eccentric orbit and two planets on circular orbits in a 2:1 configuration (Anglada-Escudé et al., 2010a); (b) between an eccentric planet and two co-orbital planets, i.e., in a 1:1 resonance or Trojan pair (Laughlin & Chambers, 2002; Giuppone et al., 2012a); (c) between a single eccentric planet and a circular planet with a long-period companion (Rodigas & Hinz, 2009); and (d) between a single eccentric planet and two near-circular planets with poorly sampled periods (e.g. HD 159868, Wittenmyer et al., 2012c).

### 2.1.5 Bayesian methods

As described in Sections 2.1.3 and 2.1.4, orbit parameters and their uncertainties are typically obtained by period searches using methods such as the Lomb–Scargle periodogram to establish the orbital period(s), and then estimating other parameters using minimisation algorithms. In practice, there are significant statistical challenges, which are complicated in the case of multiple planets by various degeneracies between orbital parameters. Determining the *number* of planets favoured by a particular data set turns out to be a non-trivial problem, posing an even greater computational challenge.

Bayesian methods, with their associated prior probabilities (see box, page 24), aim for a more rigorous approach, with advantages over more traditional methods if, for example, the data do not cover a complete orbit (e.g. Anglada-Escudé & Tuomi, 2012). They also allow a more rigorous model selection, most notably the number of planets favoured by the data (e.g. Brown, 2004;

Clyde et al., 2007; Ford & Gregory, 2007; Cumming & Dragomir, 2010; Faria et al., 2016a).

Further background to the use of Bayesian conditional probabilities for exoplanet orbit modeling, example reference priors, and the sensitivity of the detection criteria to prior choice, can be found in various studies (e.g. Tuomi, 2012; Tuomi & Anglada-Escudé, 2013).

**Priors and search space** Tuomi & Anglada-Escudé (2013), for example, take their reference set of priors to be the Keplerian parameters (radial velocity amplitude  $K$ , longitude of pericentre  $\bar{\omega}$ , eccentricity  $e$ , mean anomaly  $M_0$ , and  $\log P$ ), along with a constant reference velocity  $\gamma$ , a radial velocity jitter  $\sigma_j$  (viz., the excess white noise on top of the estimated instrument uncertainties), and a correlation coefficient between the noise of subsequent epochs  $\phi$  (as defined by Tuomi et al., 2013a,b). Typically, but not exclusively, these may be uniform over a specific interval. The planets are, in this case, assumed to be gravitationally interacting. The choice of  $\log P$  improves the sampling efficiency of parameter space, valid because of its scale invariance (Ford, 2006b).

A key problem in the application of Bayesian methods to exoplanet searches is the extensive parameter space that must be searched, and the resulting computational cost, especially in calculating the Bayesian ‘evidence’. The development of Markov Chain Monte Carlo techniques (MCMC, box, page 25) has made Bayesian methods, and probabilistic methods in general, more tractable (e.g. Gregory, 2005; Ford, 2005, 2006b; Balan & Lahav, 2009; Gregory, 2011a; Hou et al., 2012; Foreman-Mackey et al., 2013).

Nested sampling (Skilling, 2004) is a Monte Carlo method for efficient calculation of the Bayesian evidence, along with posterior inferences. It is the basis of the `MuItiNest` algorithm (Feroz & Hobson, 2008; Feroz et al., 2009a,b), which provides efficient sampling in problems that contain multiple modes and/or large degeneracies. Details of this approach in the context of exoplanet detection are given by Feroz et al. (2011b). It has been applied, for example, to 47 UMa, HD 10180, and HD 37124 (Feroz et al., 2011b), HIP 5158 (Feroz et al., 2011a), and CoRoT-7 (Faria et al., 2016a).

**Acceptance criteria** In the comparison of models with different numbers of planetary companions, Tuomi (2011) proposed that the probability density of the  $k$ -th planet should have a unique maximum that can be interpreted as a Keplerian signal (and not caused by data gaps or noise). Furthermore, the probability of confidently finding a  $k$ -th planetary signal requires that  $P(z_k) \gg P(z_{k-1})$ , where  $z$  represents the  $k$  Keplerian signals. In practice, to claim that there are  $k$  planets orbiting the target star, Tuomi (2011) has proposed that the probability of finding  $k$  signals should formally be at least 150 times greater than that of finding  $k - 1$  signals.

**Bayesian inference:** Bayesian inference (or analysis) is a method for summarising uncertainty and making estimates and predictions using probability statements conditional on observed data and an assumed model. Qualitatively, it asserts that the posterior probability of a model fit is proportional to the ‘likelihood’ times the ‘prior’.

More precisely (e.g. Feroz et al., 2011b), for a set of parameters  $\Theta$ , under a model (or hypothesis)  $H$ , and for a data set  $\mathbf{D}$ , Bayes’ theorem states that the posterior probability distribution of the parameters,  $\Pr(\Theta|\mathbf{D}, H) \equiv P(\Theta)$ , is given by

$$\Pr(\Theta|\mathbf{D}, H) = \frac{\Pr(\mathbf{D}|\Theta, H) \Pr(\Theta|H)}{\Pr(\mathbf{D}|H)}, \quad (2.32)$$

where  $\Pr(\Theta|H) \equiv \pi(\Theta)$  is the prior distribution of parameters,  $\Pr(\mathbf{D}|\Theta, H) \equiv \mathcal{L}(\Theta)$  is the sampling distribution, or ‘likelihood’, of the observed data conditional on its parameters, and  $\Pr(\mathbf{D}|H) \equiv \mathcal{Z}$  is the distribution of the observed data marginalised (in the probabilistic sense) over the parameter(s), referred to as the ‘marginal likelihood’ or ‘Bayesian evidence’.

In situations of relevance here, such an approach represents an extensive search across a wide parameter space, thus carrying a significant computational penalty.

For *parameter estimation*, the normalising evidence factor can usually be ignored, since it is independent of the parameters  $\Theta$ . Inferences can be obtained by taking samples from the (non-normalised) posterior using standard MCMC sampling methods where, at equilibrium, the chain contains a set of samples from the parameter space distributed according to the posterior. This posterior constitutes the complete Bayesian inference of the parameter values, and can be marginalised over each parameter to obtain individual parameter constraints.

For *model selection*, the evidence factor is crucial. Numerically, it is the factor normalising the posterior over the parameter set  $\Theta$  (Feroz et al., 2011b, eqn 2)

$$\mathcal{Z} = \int \mathcal{L}(\Theta) \pi(\Theta) d^D \Theta, \quad (2.33)$$

where  $D$  is the dimensionality of parameter space. Evaluation of this multi-dimensional integral is numerically challenging, with evidence evaluation being at least an order of magnitude more costly than parameter estimation alone (Feroz et al., 2011b).

There is an extensive literature on the advantages and disadvantages of Bayesian approaches (reference texts include Box & Tiao, 1992; Berger, 1985). Although less contentious when prior distributions have a physical basis or a plausible scientific model, Bayesian methods nevertheless have their critics (e.g. Gelman, 2008).

**Examples** Tuomi et al. (2013b) performed Bayesian comparisons of stellar jitter models for  $\tau$  Cet, favouring one with Gaussian noise superimposed on moving average components with exponential decay over hours to days. This resulted in significant improvements of the statistical models, and enabled the detection of signals with amplitudes below  $1 \text{ m s}^{-1}$ .

Numerous Bayesian planet searches have been reported (e.g. Gregory, 2005; Balan & Lahav, 2009; Tuomi, 2011; Nelson et al., 2014b; Tuomi et al., 2014; Brewer

& Donovan, 2015; Feng et al., 2016a; Faria et al., 2016a), leading to various candidates, amongst them HD 208487 c (Gregory, 2007a), HD 11964 b–d (Gregory, 2007b), and GJ 676 d (Anglada-Escudé & Tuomi, 2012).

Suggestions have been made for up to 4 planets around GJ 163 (Tuomi & Anglada-Escudé, 2013), up to 6 around HD 40307 (Tuomi et al., 2013a), up to 7 around GJ 667 (Anglada-Escudé et al., 2013c), up to 9 around HD 10180 (Tuomi, 2012), and up to 15 around GJ 581, although not accounting for stellar jitter (Brewer & Donovan, 2015). Many of these have not yet been independently confirmed; those that have can be assessed from the online catalogue compilations.

### 2.1.6 Algorithmic implementation

Detailed descriptions of the analysis of radial velocity data in practice is widely reported. Examples include procedures for HARPS data (e.g. Doyle et al., 2013; Triaud et al., 2013a); for Lick data (Valenti & Fischer, 2005; Wright & Howard, 2009; Howard et al., 2010a); and for CARMENES data (Trifonov et al., 2018).

**Radial velocities and orbits** Various algorithms for the determination of radial velocities, or orbits derived from them, have been described, and in several cases routines provided (for some considerations of the effects they consider, see e.g. Wright & Eastman 2014, §5). Some include a dynamical treatment. Routines include:

**EXOFAST** is a suite of IDL routines designed to fit transits and radial velocity variations simultaneously or separately, and to characterise parameter uncertainties and covariances with a differential evolution Markov Chain Monte Carlo method (Eastman et al., 2013).

**ExoSOF**T, the Exoplanet Simple Orbit Fitting Toolbox, with routines for fitting any combination of radial velocity and astrometric data (Mede & Brandt, 2017).

**Frequency Decomposer** is a parallelised algorithm for the decomposition of a noisy time series into a number of sinusoidal components (Baluev, 2013b).

**Keplerian periodogram**, in which the signal is modeled by a highly non-linear Keplerian radial velocity function (Baluev, 2015b), a formulation claiming significant efficiency gains with respect to the Lomb–Scargle periodogram, especially for high-eccentricity orbits.

**PlanetPack** for the analysis of radial velocity data with unknown jitter, employing multiple Keplerian orbits or dynamical N-body simulations (Baluev, 2013d,e, 2014).

**PyORBIT** for radial velocity time series and ancillary data (such as photometry and activity indicators) to simultaneously characterise the orbital parameters and the host star activity (Malavolta et al., 2016).

**rvfit** for fitting radial velocities of stellar binaries and exoplanets using ‘adaptive annealing’ global minimisation methods (Iglesias-Marzoa et al., 2015b,a).

RVLIN (IDL) for fitting an arbitrary number of Keplerian curves (Wright & Howard, 2012), and BOOTTRAN for the corresponding errors (Wang & Wright, 2012).

SERVAL, Spectrum Radial Velocity Analyser, is a least-squares algorithm to derive radial velocities and additional spectral diagnostics (Zechmeister et al., 2018).

Spectroscopy Made Easy for synthetic spectral fitting (e.g. Valenti & Piskunov, 1996; Kane et al., 2011c).

Stacked Bayesian Lomb-Scargle periodogram for identifying periodicities caused by stellar activity (Mortier & Collier Cameron, 2017).

Systemic Console for computing Keplerian fits (e.g. Meschiari et al., 2009; Meschiari & Laughlin, 2010; Jones et al., 2013b; Vogt et al., 2014b).

**Advanced search schemes** Because the equations describing an astrometric or radial velocity orbit are non-linear, unstructured searches of parameter space for multiple planets may be computationally prohibitive, and with many false local  $\chi^2$  minima. More sophisticated search schemes are therefore desirable. Amongst those widely used are numerical schemes based on genetic algorithms, Levenberg–Marquardt minimisation, and Markov Chain Monte Carlo methods.

Some early searches used *genetic algorithms* to explore global parameter space (e.g. Goldberg, 1989; Charbonneau, 1995), e.g. for  $\nu$  And (Butler et al., 1999; Stepinski et al., 2000), GJ 876 (Laughlin & Chambers, 2001), 55 Cnc (Marcy et al., 2002), HD 12661 (Goździewski & Maciejewski, 2003, PIKAIA), and  $\mu$  Ara (Pepe et al., 2007, Stakanof). According to Stepinski et al. (2000) and Goździewski & Maciejewski (2003), the method is inefficient in identifying very accurate best-fit solutions, but provides good starting points for more precise gradient methods such as Levenberg–Marquardt.

The *Levenberg–Marquardt method* is an efficient algorithm for finding a local  $\chi^2$  minimum for non-linear models. It varies smoothly between ‘steepest descent’ far from the minimum, and the inverse-Hessian method as a minimum is approached. It has been widely used for both radial velocity and astrometric orbit fitting. Implementations include `mrqmin` (Press et al., 2007).

Due to sparse sampling, measurement errors, parameter degeneracy and model limitations, there are frequently no unique values of the basic model parameters such as period and eccentricity, and a Bayesian approach (§2.1.5) can provide more robust estimates of parameter uncertainties. The *Markov Chain Monte Carlo method* (MCMC) has been widely used for orbit fitting for radial velocity observations, as well as for photometric transit light curves (box, page 25).

**Algorithms** Amongst available algorithms:

EXOFIT: is a Bayesian tool employing a Markov Chain Monte Carlo method, and specifically tailored to exoplanet radial velocity fitting for a one- or two-planet sys-

**Markov Chain Monte Carlo, MCMC:** Probabilistic data analysis, including Bayesian inference (§2.1.5), has transformed many areas of research in the past decade. Significant gains have come from numerical methods for approximate inference, especially Markov Chain Monte Carlo (MCMC; Metropolis et al., 1953; Hastings, 1953).

Probabilistic data analysis procedures involve computing and using the posterior probability density function for the parameters of the model or the likelihood function. In some cases it is sufficient to find the maximum of one of these, but it is often necessary to understand the posterior probability density function in detail. MCMC methods are designed to sample from, and thereby provide sampling approximations to, the posterior probability density function efficiently, even in parameter spaces with large numbers of dimensions. MCMC links two concepts: the Markov Chain, being a random process with the property that the future depends only on the current state of the process and not the past (i.e. it has no memory); and Monte Carlo methods, which randomly sample from some underlying process to provide an estimate of something too complex or time consuming to find deterministically.

The two concepts are put together to construct a Markov Chain which converges to the desired probability distribution after a number of steps. The state of the chain is used as a sample from the desired distribution, and the process is repeated. MCMC algorithms use different techniques for generating/sampling the Markov Chain (e.g. those of Metropolis–Hastings; Gibbs; or Goodman–Weare).

Numerous MCMC algorithms are used in the exoplanet community, including `emcee` (Foreman-Mackey et al., 2013); `MC3` (MCCubed), Multi-Core Markov-Chain Monte Carlo (Cubillos et al., 2016b, 2017c); and `GEMC`, based on DE–MC (Tregloan-Reed et al., 2018). Specific optimisations for exoplanet studies have been developed (e.g. Ford, 2004b; Gregory, 2005; Ford, 2006b; Gregory, 2007a,b; Carter et al., 2011c). Of many example applications, Gregory & Fischer (2010) describe parallel tempering, simulated annealing, and genetic crossover applied to 47 UMa; Gregory (2011a) describe efficient sampling in highly correlated parameter spaces; and Triaud et al. (2011) describe fitting to WASP light curves.

More complete discussion of MCMC methods can be found in, e.g., Mackay (2003), while key concepts in this context are summarised by Foreman-Mackey et al. (2013).

tem (Balan & Lahav, 2009, 2011). A uniform analysis of 94 systems was carried out by Hollis et al. (2012).

`Joker`: a Monte Carlo sampler for sparse or noisy radial velocity measurements of a 2-body system (Price-Whelan et al., 2017).

`MPFIT`: an IDL implementation of Levenberg–Marquardt minimisation (Markwardt, 2009). One of many applications to radial velocity fitting is described, for example, by Wright & Howard (2009).

`RUN DMC` is a parallel code for analysing radial velocity observations using N-body integrations and differential evolution MCMC (Nelson et al., 2014a). Application to 55 Cnc involving both radial velocity and transit observations is described by Nelson et al. (2014b).

### 2.1.7 Detectability and selection effects

Various studies have been made of planet detectability from radial velocity data as a function of period and signal amplitude (e.g. Nelson & Angel, 1998; Eisner & Kulkarini, 2001b; Cumming, 2004; Narayan et al., 2005).

Cumming (2004) provides analytic expressions for planet detectability as a function of period and eccentricity, and some insight into the detection limits. For short orbital periods,  $P \lesssim T$  where  $T$  is the duration of the observations, the radial velocity semi-amplitude threshold alone characterises detectability. At long periods,  $P \gtrsim T$ , the observations cover only part of the orbit by definition, and detectability depends on which part of the orbit is being sampled. If the orbit is close to a velocity maximum/minimum, or to a zero crossing, velocity variations are ‘sine-like’ or ‘cosine-like’ respectively, and the velocity variations are

$$\Delta v = K \sin\left(\frac{2\pi T}{P}\right) \approx K\left(\frac{2\pi T}{P}\right), \quad \text{or} \quad (2.34)$$

$$\Delta v = K \cos\left(\frac{2\pi T}{P}\right) \approx \frac{K}{2}\left(\frac{2\pi T}{P}\right)^2 \quad (2.35)$$

respectively. Averaging over phase introduces a dependency on the adopted detection efficiency,  $\epsilon_D$ : for  $\epsilon_D = 0.5$ , the amplitude must be large enough that sine-like phases are detected, but cosine-like phases do not have to be, and the velocity threshold scales as  $K \propto P$ . For  $\epsilon_D = 0.99$ , almost all phases must be detected, requiring a large amplitude, which then scales as  $K \propto P^2$ .

While the dependence of  $K$  on  $e$  given by Equation 2.27 results in large  $K$  for highly eccentric orbits, in practice eccentricity acts to make detection more difficult at short periods, where an uneven sampling often results in poor phase coverage during rapid pericentre passages. At longer periods, the increased velocity amplitude and acceleration near the pericentre increase detectability. The transition to the long-period regime occurs for orbital periods  $P \approx T/(1-e)^2$ . The analysis also allows the completeness of existing surveys to be assessed (Cumming et al., 2008). The results emphasise that there remains a significant selection effect against detecting eccentric orbits for  $e \gtrsim 0.6$ .

Shen & Turner (2008) found that, once a planet is detected, the eccentricities derived from Keplerian fitting are biased upwards for low signal-to-noise and moderate numbers of observations. They suggest that the numbers of exoplanets with low-eccentricity may be underestimated in current samples. The effect may be evident in results from Keck, for example, where for  $P > 10$  d the observed eccentricity distribution is nearly flat for large-amplitude systems,  $K > 80 \text{ m s}^{-1}$ , but rises linearly towards low eccentricity at lower amplitudes,  $K > 20 \text{ m s}^{-1}$  (Valenti et al., 2009).

Rodigas & Hinz (2009) showed that there is an additional bias due to the presence of an undetected outer

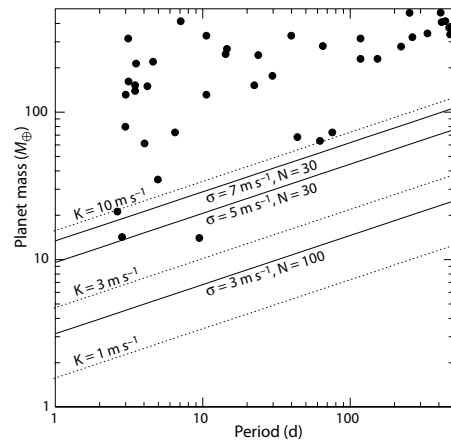


Figure 2.6: Minimum mass limits for a 50% detection threshold as a function of the number of observations,  $N$ , and the combined error (measurement and stellar jitter)  $\sigma$ , for  $M_\star = 1 M_\odot$  (Equation 2.36). The observation duration is assumed longer than  $P_{\text{orb}}$ . Circles are planets known in 2005. Dotted lines show various radial velocity semi-amplitudes,  $K$ . From Narayan et al. (2005, Figure 7), by permission of IOP Publishing/AAS.

companion. For moderate eccentricity  $0.1 < e < 0.3$ , for example, there is a 13% probability that a modeled eccentric orbit is in fact circular, with the model fit confused by the undetected outer companion.

Narayan et al. (2005) evaluated the detection probability for low mass planets, either in isolation or near mean motion resonance with a hot Jupiter. For a 50% detection rate their expression for the minimum detectable mass is

$$M_{p,\text{min}} \sim 4 M_\oplus \left(\frac{N}{20}\right)^{-\frac{1}{2}} \left(\frac{\sigma}{1 \text{ m s}^{-1}}\right) \left(\frac{P}{1 \text{ d}}\right)^{\frac{1}{3}} \left(\frac{M_\star}{M_\odot}\right)^{\frac{2}{3}}, \quad (2.36)$$

for  $N \gtrsim 20$ , where  $N$  is the number of observations, and  $\sigma$  is the quadratic sum of the Doppler velocity measurement error and stellar jitter (Figure 2.6).

### 2.1.8 Scheduling

In a study for the Space Interferometric Mission SIM, Ford (2004a) considered several non-adaptive observing schedules (i.e. schedules fully defined *a priori*) for a targeted astrometric planet search. These included time intervals which are regular periodic (at constant spacing); Golomb ruler<sup>8</sup>; regular power law; regular logarithmic; regular geometric; and random uniform. The efficiency for planet searches was found to be relatively insensitive to the actual observing schedule.

<sup>8</sup>A Golomb ruler has unique integer intervals between each pair of marks, thus providing the maximum number of unique baselines. The number of marks defines its order; it is ‘perfect’ if it includes all distances up to its length, and ‘optimal’ if no shorter ruler of that exists. Thus the (optimal and perfect) Golomb ruler of order 4 and length 6 has marks at 0, 1, 4, 6.

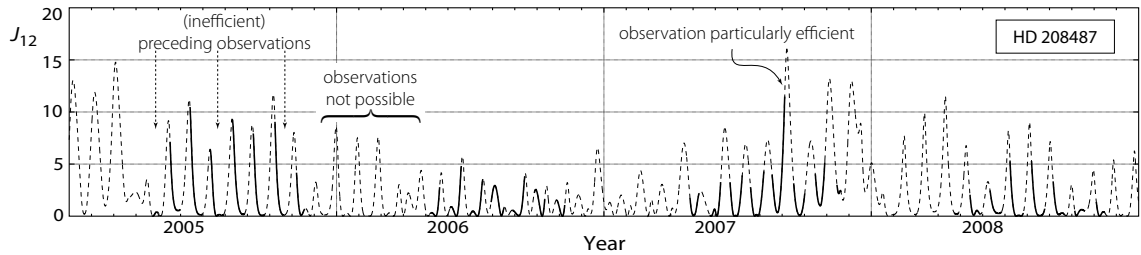


Figure 2.7: Scheduling future radial velocity observations to discriminate between two orbit models for HD 208487. The parts of the curve shown dashed correspond to times when observations are impossible. Observations are optimal when scheduled to coincide with the information peaks  $J_{12}$ . Arrows mark the three preceding radial velocity measurements, which in retrospect are seen to have been of little additional information value. From Baluev (2008b, Figure 2), © Oxford University Press.

*Adaptive scheduling*, in which information from previous observations is used to plan future ones most efficiently, can optimise their information content, and can perform significantly better. The objective is to predict future epochs which yield, for example, maximum improvement in orbit parameters and planet masses, the most favourable epochs for distinguishing between alternative models, or an optimum series of future observations. For multiple planet systems, and in particular for resonant orbits, such optimal timings may be concentrated in rather narrow time intervals.

**Examples** Loredo (2004) outlined a maximum entropy sampling strategy for determining an exoplanet orbit based on Bayesian inference, and Ford (2008) developed a more rigorous adaptive scheduling algorithm exploiting information theory. Based on a small number of initial observations, this proceeds by assuming a prior for the distribution of orbital periods and masses, using Bayesian inference to calculate the posterior probability distribution for all model parameters, using this to calculate the predictive distribution for the radial velocities at some future time, and finally choosing observing times at which additional observations would be most valuable. Monte Carlo simulations demonstrated that such searches are more efficient in terms of detection, and can measure orbital parameters more accurately, than non-adaptive algorithms.

Baluev (2008b, 2010) used criteria from optimal design theory (based on Fisher information, Shannon information, and Kullback–Leibler divergence) to design similar general scheduling formalisms. As an example, Figure 2.7 illustrates the problem of deciding between two orbital solutions based on the 35 measurements of HD 208487 from Butler et al. (2006b). Wright et al. (2007) identified periodicity attributable to an additional planet at either 28.6 or 900 d, but their data was inadequate to rule between them due to aliasing.

If the probability densities  $p_{1,2}(v)$  describe the distribution of the radial velocity predictions for two possible orbit fits, the expectation of the likelihood ratio statistic considering the first or the second model as true

are given by (Baluev, 2008b, eqn 3)

$$I_{2|1} = \int p_1(v) \ln \frac{p_1(v)}{p_2(v)} dv, \quad I_{1|2} = \int p_2(v) \ln \frac{p_2(v)}{p_1(v)} dv \quad (2.37)$$

The maximum information is given by (Baluev, 2008b, eqn 11)

$$J_{12} = I_{2|1} + I_{1|2} \quad (2.38)$$

$$= -1 + \frac{1}{2} \left( \frac{\sigma_1^2}{\sigma_2^2} + \frac{\sigma_2^2}{\sigma_1^2} \right) + \left( \frac{1}{\sigma_1^2} + \frac{1}{\sigma_2^2} \right) \frac{(v_1 - v_2)^2}{2},$$

under the assumption that the distributions of  $v_i$  are close to Gaussian. The largest values of  $J_{12}$  then correspond to the most promising times for future observations to rule out one of the alternative models. Although Equation 2.38 is derived by Baluev (2008b) from a formal consideration of information content, its interpretation is straightforward: observations should be made when the two models imply the largest predicted differences in the measured radial velocity, while the uncertainties of these predictions,  $\sigma$ , should be small enough to avoid statistically insignificant differences.

For HD 208487 (Figure 2.7) the radial velocity predictions for the two different orbit models differ by up to  $20 \text{ m s}^{-1}$ . The function  $J_{12}$  identifies the epochs which maximise discrimination between them. It turns out that a single observation at one of the peaks during the 2005 observing season could have decided between competing models at the  $\geq 2\sigma$  level, while the actual observations (indicated by arrows) fell at epochs of low information content, and added little new to the contested two-planet solution. The subsequent season (2006) offered limited opportunity for further discrimination.

Further considerations in optimal scheduling are given by Pál (2009). The scheduling of CARMENES observations is described by Garcia-Piquer et al. (2017).

**Survey optimisation** Bottom et al. (2013) examined statistical and instrumental effects with the goal of maximising planet detection yields for a fixed observing time. They showed that G and K dwarfs observed at 400–600 nm are optimum for surveys targeting completeness to a given  $M_p$  and  $P_{\text{orb}}$ , while M dwarfs observed at 700–800 nm are optimum for habitable-zone planets.

## 2.2 Measurement principles

### 2.2.1 Doppler shifts

An instantaneous measurement of the stellar radial velocity about the star–planet barycentre is given by the small, systematic Doppler shift of the many absorption lines that make up the stellar spectrum.

If, in the observer’s reference frame, the source is receding with velocity  $v$  at an angle  $\theta$  relative to the observer–source direction, the change in wavelength

$$\Delta\lambda = \lambda_{\text{obs}} - \lambda_{\text{em}}, \quad (2.39)$$

is related to the velocity by the expression for the relativistic Doppler shift (e.g. Lang, 1980, eqn 2–226)

$$\lambda_{\text{obs}} = \lambda_{\text{em}} \frac{(1 + \beta \cos\theta)}{(1 - \beta^2)^{1/2}}, \quad (2.40)$$

where  $\lambda_{\text{obs}}, \lambda_{\text{em}}$  are observed and emitted wavelengths, and  $\beta = (v/c)$ . For  $v \ll c$  and  $\theta \ll \pi/2$ , the expression reduces to the classical form

$$v_{\text{r}} = v \cos\theta \approx \left( \frac{\Delta\lambda}{\lambda_{\text{em}}} \right) c, \quad (2.41)$$

where, conventionally, positive values indicate recession. Special relativistic terms correspond to changes in  $v_{\text{r}}$  of several  $\text{m s}^{-1}$ , and are therefore significant. Equation 2.40 omits the effect of the refractive index of air at the spectrograph,  $n_{\text{air}}$  (1.000 277 at standard temperature and pressure, STP), which introduces errors of  $\lesssim 1 \text{ m s}^{-1}$  (Marcy & Butler, 1992, eqn 3).

With the radial velocity semi-amplitude values of  $K_{\text{J}} \approx 12.5 \text{ m s}^{-1}$  and  $K_{\oplus} \approx 0.09 \text{ m s}^{-1}$  as indicative goals, the detection of planets around solar-type stars has demanded long-term radial velocity accuracies of some  $15 \text{ m s}^{-1}$  or preferably significantly better, corresponding to an accuracy of a few parts in  $10^8$  in wavelength. This must be maintained over months or years.

High-accuracy radial velocities for exoplanet detection are typically acquired using échelle spectrographs with high spectral resolving power (typically  $R \equiv \lambda/\Delta\lambda \sim 50\,000 - 100\,000$ ), and operated in the optical region (450–700 nm). Many diffraction orders are cross-dispersed, and recorded simultaneously on rectangular format CCDs providing large numbers of resolved absorption lines (Figure 2.8). The principles of an échelle spectrograph are described by, e.g., Vogt (1987) in the case of the Lick Observatory Hamilton spectrometer, by Vogt et al. (1994) in the case of Keck–HIRES, and by Baranne et al. (1996) in the case of ELODIE.

High instrumental stability and accurate wavelength calibration is demanded to minimise effects of gravitational and thermal telescope flexure, and other instrument drifts. Large telescopes and long integration times are still required to achieve the necessary high signal-to-noise, and corresponding sub-pixel accuracies.

### 2.2.2 Spectral resolution

For unresolved spectral lines, measurement precision increases with improved spectral resolution (Bouchy et al., 2001). In the photon-noise limited regime the error  $\epsilon$  on the line-centre measurement can be approximated by (Pepe et al., 2014a)

$$\epsilon = \frac{\sigma^{1.5}}{(2I_0)^{0.5} \cdot \sigma\mathcal{C}} \left( 1 - \frac{\mathcal{C}}{2} \right)^{\frac{1}{2}}, \quad (2.42)$$

where  $\sigma$  is the spectral line width observed through the spectrograph,  $\mathcal{C} = (I_{\text{min}} - I_0)/I_0$  is the line contrast (where  $I_0$  and  $I_{\text{min}}$  are the photoelectron counts per resolution element in the continuum and line minimum respectively), and  $\sigma\mathcal{C}$  is the equivalent width.

A spectral resolution of at least  $R \equiv \lambda/\Delta\lambda = 100\,000$  has been found to provide the best precision on slowly-rotating, quiet, solar-type stars. High spectral resolution and adequate line sampling provide better signal-to-noise per spectral line, and also lead to smaller instrumental errors in both the radial velocity measurement and the calibration process (Bouchy et al., 2001).

Some recent instruments for 8-m class telescopes or larger have adopted significantly higher resolutions of  $R = 200\,000 - 300\,000$ , notably PEPSI (optical) and iLocater (near infrared), both for the LBT, and complementary in their wavelength coverage (Table 2.4).

**Ultra-high spectral resolution** Throughput is an important requirement, and ultra-high resolution spectrographs (e.g. the  $R = 10^6$  AAT–UHRE, Diego et al. 1995; or the  $R = 600\,000$  échelle at Steward Observatory, Ge et al. 2002a) do not provide the efficiencies of  $\gtrsim 10\%$  needed for competitive planet searches.

**Extremely large telescopes** To first order, instrument errors scale with the resolution element expressed in wavelength units (Pepe et al., 2014a). However, with increasing telescope size, spectral resolution becomes a cost driver. For seeing-limited instruments, the optical étendue (i.e. beam cross section area times solid angle,  $E = A\Omega$ ) increases with telescope size, and so does the instrument size for a given spectral resolution. For 8-m and extremely-large telescopes, this aspect has become a technical and managerial challenge requiring novel, compact designs (Pasquini et al., 2010; Pepe et al., 2014b; Szentgyorgyi et al., 2012; Marconi et al., 2016).

### 2.2.3 Cross-correlation spectroscopy

Information about the instantaneous Doppler shift is contained in the many thousands of absorption lines in the high-resolution optical spectrum of solar-type stars. This information can be concentrated into a few parameters by cross-correlation, even at low signal-to-noise (Figure 2.9). This involves multiplying the stellar spectrum by a weighted (binary) mask, and finding the minimum of the product as a function of the Doppler shift.



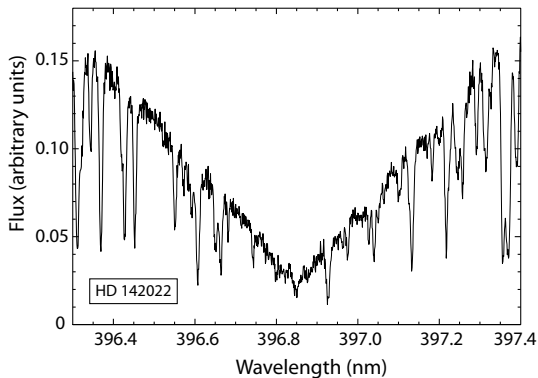


Figure 2.8: The Ca II H absorption-line region of the HARPS échelle spectrum for HD 142022, illustrating the density of lines in 1 nm of the 378–691 nm spectrum. From Eggenberger et al. (2006, Figure 1), reproduced with permission © ESO.

The technique, originally implemented using a physical mask, was proposed by Fellgett (1955), first demonstrated by Griffin (1967), and extended to échelle spectroscopy using CORAVEL by Baranne et al. (1979). As Fellgett phrased it, ‘It is uneconomical, both in telescope time and in labour of reduction, to observe the details of a stellar spectrum if the sole object of the observation is to measure a radial velocity.’

Limitations of a fixed physical template, in accuracy and adaptability to spectral type, led to the cross-correlation subsequently implemented numerically as a box-shaped template (Queloz, 1995; Baranne et al., 1996). Finer details of the method have been developed progressively (e.g. Simkin, 1974; Sargent et al., 1977; Tonry & Davis, 1979; Bender, 1990). The essentials are to determine the value of  $\epsilon$  minimising (Queloz, 1995)

$$C(\epsilon) \propto \int_{-\infty}^{+\infty} S(v) M(v - \epsilon) dv, \quad (2.43)$$

where  $S$  is the spectrum and  $M$  is the mask, both expressed in velocity space  $v$ . Associated errors are established from Monte Carlo modeling. Weighting according to the relative line depths further optimises the signal-to-noise, and can also reduce the perturbing effects of telluric lines (Pepe et al., 2002).

The precise shape of the resulting *cross-correlation function* depends on the intrinsic spectral line shapes and on the template line widths, and overall represents a mean profile of all lines in the template. Accordingly, in addition to the radial velocity, the width yields the stellar rotational velocity  $v \sin i$ , while the equivalent width provides a metallicity estimate if  $T_{\text{eff}}$  is known approximately (Mayor, 1980; Benz & Mayor, 1981; Queloz, 1995). In the absence of systematic line asymmetry, the underlying shape of the cross-correlation function is well approximated by a Gaussian, with asymmetry reflecting systematic structure in the individual spectral lines.

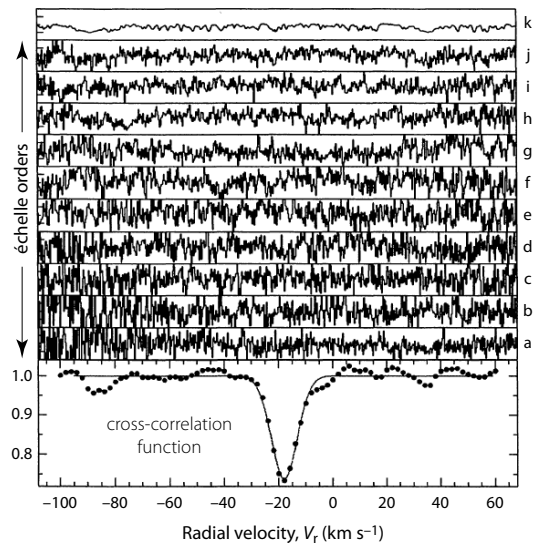


Figure 2.9: Example cross-correlation function for a K0 III star with  $S/N = 1$ . Observations at  $R = 40000$  span 411–444 nm in ten orders, each covering 4 nm. Some 1000 lines match the template. The top trace is the same order as that immediately below, but at  $S/N = 40$ . The cross-correlation function is shown at bottom. From Queloz (1995, Figure 2).

For HARPS data, an alternative to cross-correlation is based on least-squares matching of each observed spectrum to a high signal-to-noise ratio template derived from the same observations. Thus, HARPS TERRA (Template-Enhanced Radial velocity Re-analysis Application) reports a significant improvement in accuracy, especially for M dwarfs (Anglada-Escudé & Butler, 2012), where a mean activity jitter of  $2.3 \text{ m s}^{-1}$  has been reported for a sample of 78 stars (Perger et al., 2017a).

## 2.2.4 Determination of barycentric velocities

The measured Doppler shift, Equation 2.39, in practice includes effects other than the line-of-sight velocity of the target star’s centre of mass. Contributions from the motion of the observer around the solar system barycentre, due to Earth rotation and orbital motion, are time varying, significant at levels of up to 0.5 and  $30 \text{ km s}^{-1}$  respectively, and must be accounted for.

Higher-order relativistic and secular projection effects, and additional spectroscopic line shifts introduced by gravitational redshift and stellar surface effects such as convective flow, pulsations, and star spots (Dravins, 1975; Nidever et al., 2002; Lindgren & Dravins, 2003) may be less critical in determining the relative radial velocities central to exoplanet detection. But there are situations where their contributions must be considered, and all must be accounted for in any *absolute* determination of radial space motion at the  $\text{m s}^{-1}$  level. The magnitude of these effects is as follows.

**Barycentric correction** To detect changes in a star's radial velocity due to an orbiting planet, measured velocities must be referred to a non-moving frame, or at least one with a constant rectilinear space motion. The *solar system barycentre* (i.e. the solar system's centre of mass, as opposed to the Sun's centre of mass or *heliocentre*) is consequently adopted as reference. For details see, e.g., Wright & Eastman (2014, §3.2).

The time-varying motion of the Earth around the barycentre, which includes gravitational perturbations from the other planets, is described by the *solar system ephemerides* provided by JPL (e.g. Konopliv et al., 2006) and IMCCE (e.g. Fienga et al., 2008, 2009, 2014). By adjusting for known effects, residual velocity terms were brought below  $1 \text{ m s}^{-1}$  (cf. Stumpff, 1980), and now routinely to below  $0.01 \text{ m s}^{-1}$  (Wright & Eastman, 2014).

Nonetheless a spurious one-year signal in the HARPS data, at an amplitude of a few  $\text{m s}^{-1}$ , was only recently traced to the deformation of spectral lines crossing block stitchings of the CCD as the Earth orbits the barycentre (Dumusque et al., 2015b).

**Earth rotation, precession, nutation** These effects are important at levels of  $\sim 0.01 \text{ m s}^{-1}$ . They are discussed, for example, by Wright & Eastman (2014, §6.2.1).

**Stellar space motion** Effects of a star's radial motion on the secular evolution of its parallax and proper motion are treated by Dravins et al. (1999), and encapsulated in Equations 3.13–3.14. Equivalently, a constant space motion results in a changing radial velocity with time due to the changing projection geometry.

Knowledge of the star's parallax  $\varpi$ , proper motion  $\mu$ , and systemic radial velocity  $\gamma$ , allows prediction of this contribution to any secular evolution, which might otherwise be attributed to long-period planetary orbits.

For Barnard's star, observed with VLT-UVES over five years (Figure 2.10), Kürster et al. (2006) measured a secular radial velocity acceleration consistent with the predicted value of  $4.50 \text{ m s}^{-1} \text{ yr}^{-1}$  based on the Hipparcos proper motion and parallax, combined with the absolute radial velocity of  $-110.5 \text{ km s}^{-1}$  (Nidever et al., 2002). An increase of  $4.515 \pm 0.002 \text{ m s}^{-1} \text{ yr}^{-1}$  was determined from Lick and Keck observations over 25 years between 1987 and 2012 (Choi et al., 2013a).

**Gravitational redshift** The contribution from the star's *gravitational redshift* is given by (e.g. Misner et al. 1973, eqn 25.26N; Lang 1980, eqn 2–234)

$$v_{\text{r}} \simeq \frac{GM_{\star}}{R_{\star} c}. \quad (2.44)$$

This is valid in the Newtonian limit,  $R_{\star} \gg R_{\text{S}}$ , where the Schwarzschild radius  $R_{\text{S}} \equiv 2GM_{\star}/c^2$ . The contribution amounts to  $636 \text{ m s}^{-1}$  for the Sun, and ranges from  $\sim 680 \text{ m s}^{-1}$  at F5V to  $\sim 500 \text{ m s}^{-1}$  at M5V, and several tens of  $\text{km s}^{-1}$  for white dwarfs. Effects due to *changes* in gravitational redshift are discussed in Section 2.5.1.

**Stellar rotation** Stellar rotation imposes small radial velocity effects (Gray, 1999), while the contribution of variable meridional flows may be comparable (Beckers, 2007). More critical at high accuracies are the effects of surface features such as star spots, which can induce a radial velocity amplitude of a few  $\text{m s}^{-1}$  (e.g. Saar & Donahue, 1997; Hatzes, 2002), resulting in periodic modulation at the stellar rotation period (§2.4.5).

**Stellar convection** Convective motion in the photospheres of cool stars leads to spectral line asymmetries (§2.4.6). A net blueshift results from the contribution of photons from the larger and brighter photospheric granules compared with the downward motion in the darker and cooler intergranular lanes.

The effect is of order  $-0.5 \text{ km s}^{-1}$  for the Sun and other solar-type stars, and ranges from  $-1000 \text{ m s}^{-1}$  at F5V to about  $-200 \text{ m s}^{-1}$  at K0V (Dravins et al., 1981). Effects due to pressure broadening are  $\leq 100 \text{ m s}^{-1}$  for main sequence stars (Dravins, 1999). Corrective approaches are detailed by Meunier et al. (2017).

**Stellar activity** This is considered in Section 2.4.5.

**Observatory-related effects** Also relevant are potential timing errors (box, page 104) and, at the highest target accuracies, effects such as atmospheric chromatic aberration (Blackman et al., 2017), and errors associated with imperfect knowledge of the telescope position.

**Higher-order source effects** Various higher-order effects, including gravitational redshift variations due to change in stellar radius, Zeeman effect, and planet-induced tides, are considered in Section 2.5.3.

**Radial velocity zero point** As a result of these astrophysical and instrumental effects, establishing the zero point for absolute radial motions at  $\leq 50 \text{ m s}^{-1}$  remains difficult. Nidever et al. (2002) determined barycentric radial velocities for 889 late-type stars observed at Keck and Lick with typical accuracies of  $0.3 \text{ km s}^{-1}$ , and found a difference in zero point of  $53 \text{ m s}^{-1}$  compared with the system of the 38 stable FGK stars adopted as standards by the Geneva group (Udry et al., 1999a,b).

**Practical implementation** For the detection of Earth analogues, with reflex motion  $\sim 0.09 \text{ m s}^{-1}$ , collective correction of the above effects to  $\leq 0.01 \text{ m s}^{-1}$  is implied. Such accuracies are targeted with E-ELT-HIRES, at least in the context of the 'Sandage test' (§2.6.6).

Wright & Eastman (2014) describe the theory and implementation of many of the above terms at levels of  $\sim 0.01 \text{ m s}^{-1}$ , including those arising from the Earth's rotation and orbital motion, the relative motion of the solar system with respect to target star, relativistic effects, atmospheric chromatic aberration, and errors associated with imperfect knowledge of the telescope position, timing, stellar position and space motion.

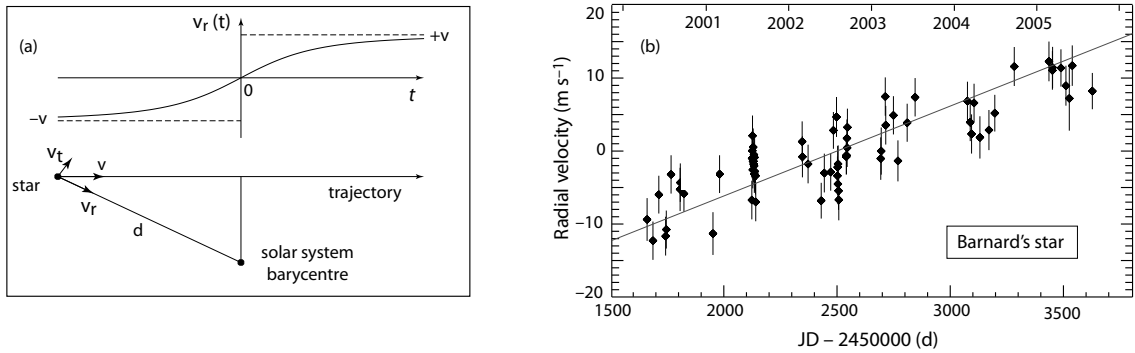


Figure 2.10: Geometry of the space motion of a nearby star. In (a), bottom panel,  $v_t$  and  $v_r$  are, respectively, the transverse and radial components of the space velocity  $v$ , and  $d$  is the current distance; (a, top) absolute radial velocity as a function of time and its asymptotic limits  $\pm v$ . (b) barycentric radial velocity measurements of Barnard's star over five years, compared with the predicted secular acceleration (solid line). Adapted from Kürster et al. (2003, Figure 1) and Kürster et al. (2006, Figure 3).

### 2.3 Wavelength calibration

Accurate wavelength calibration is a prerequisite for reaching high radial velocity accuracy. In the early 1970s, accuracies of around  $1 \text{ km s}^{-1}$  were limited by photographic plate technology, and by guiding errors at the spectrograph slit which introduced shifts in the stellar spectrum relative to comparison arc lines.

#### 2.3.1 Telluric lines

Wavelength calibration was significantly improved by the use of telluric (atmospheric) water vapour lines (Griffin, 1973; Griffin & Griffin, 1973; Walker et al., 1973; Gray & Brown, 2006), largely eliminating errors caused by the different optical paths of the stellar beam and the calibration lamp. Disadvantages include limited spectral ranges where telluric lines of suitable strength are found, in addition to various systematic errors arising from variable path length as a function of zenith distance, producing variations of  $20 \text{ m s}^{-1}$  per air mass, and from significant winds, producing systematic shifts of  $20 \text{ m s}^{-1}$  (Gray & Brown, 2006).

Analysis of HARPS archival data over 6 years for the bright stars  $\tau$  Cet,  $\mu$  Ara, and  $\epsilon$  Eri suggested a long-term stability of atmospheric lines of  $\sim 10 \text{ m s}^{-1}$ . A simple atmospheric model yielded short-term stability of  $\sim 2 \text{ m s}^{-1}$  (Figueira et al., 2010b).

#### 2.3.2 Gas cells

The use of captive gases to provide a dense and accurate wavelength reference, superimposed on the stellar spectral lines, started with the use of hydrogen fluoride (HF). Although toxic and corrosive, its 3–0 vibration band gave a well-spaced line distribution, with no isotopic confusion, and of similar natural width to those in typical stellar spectra (Campbell & Walker, 1979).

An alternative, iodine ( $\text{I}_2$ ), also mononuclidic, was used by Beckers (1976) and Koch & Woehl (1984) for solar observations, and later by Marcy & Butler (1992) for their radial velocity programme at the Lick Observatory 3-m telescope (a retrospective is given by Beckers, 2005). It has a strong line absorption coefficient, and requires a path length of only a few cm. Accuracies improved accordingly, to around  $25 \text{ m s}^{-1}$  by the early 1990s, and to some  $3 \text{ m s}^{-1}$  just a few years later (Butler et al., 1996).

The gas cell is placed in the telescope light path, just before the spectrograph slit. Sharp absorption lines of known wavelength are superimposed on the stellar spectrum, thereby providing calibration of both wavelength and the spectrograph point-spread function. For an échelle, the latter is complex with many degrees of freedom (Valenti et al., 1995).

The spectrum through the absorption cell is then modeled as (Marcy & Butler, 1992, and their figure 1)

$$I_{\text{obs}}(\lambda) \propto [I_{\star}(\lambda + \Delta\lambda_{\star})T_{\text{I}_2}(\lambda + \Delta\lambda_{\text{I}_2})] \otimes \text{PSF}, \quad (2.45)$$

where  $\Delta\lambda_{\star}$  and  $\Delta\lambda_{\text{I}_2}$  are the shifts of the star spectrum and iodine transmission function, determined by least-squares fitting to the composite spectrum,  $I_{\text{obs}}$ ; and  $\otimes \text{PSF}$  represents convolution with the spectrograph point-spread function.  $I_{\star}$ , via  $I_{\star} \otimes \text{PSF}$ , is obtained *a priori* by observing each star without the iodine cell in place. The iodine cell transmission function,  $T_{\text{I}_2}$ , is obtained from external measurements using a high-resolution Fourier transform spectrometer. The final corrected Doppler shift is then given by  $\Delta\lambda = \Delta\lambda_{\star} - \Delta\lambda_{\text{I}_2}$ .

Modified calibration sequences have been developed. Iterating from an existing spectral template of a similar star can eliminate the need for an observed stellar template spectrum (Johnson et al., 2006c). Modified calibration sequences to measure binary stars, and in particular double-lined spectroscopic binaries, are described by Konacki (2005b).

The iodine gas cell remains the standard in many instruments (including AAT-UCLES, HET-HRS, Keck-HIRES, Lick 3 m, Magellan-MIKE, OAO-HIDES, Subaru-HDS, Tautenburg, TNG-SARG, and VLT-UVES), being of particular relevance for spectrographs which are not intrinsically highly stabilised. Alternative implementation strategies also exist (Johnson et al., 2006c).

The advantages of the iodine absorption cell are the large number (several thousand) of absorption lines, and the common path of the starlight and the iodine absorption. The measured iodine lines therefore simultaneously track changes in the instrument point-spread function. The disadvantages are the 20–30% loss of light, and the clustering of the absorption-line bands in the visible (500–620 nm), making wavelength calibration for redder M dwarfs more problematic.

### 2.3.3 Emission lamps

ELODIE (Baranne et al., 1996), and its successor HARPS (Mayor et al., 2003), used a thorium–argon (Th–Ar) emission lamp as the reference wavelength spectrum. In practice, two optical fibers are used to transfer light to the spectrograph, one collecting the stellar light, the other simultaneously recording either a Th–Ar reference spectrum, or the background sky.

The advantages of the Th–Ar lamp for wavelength calibration are the large numbers of strong emission lines over a wide optical to infrared range (Palmer & Engleman, 1983; Hinkle et al., 2001; Lovis & Pepe, 2007; Kerber et al., 2008), and the improvement in throughput due to the absence of the iodine absorption cell.

In addition to the use of the Th–Ar lamps, CARMENES is also using U–Ne lamps, which provide a higher line density in the near infrared (Redman et al., 2011, 2012), and suffer less from excessively bright (overexposed) noble gas lines (Quirrenbach et al., 2012).

Given the significant ageing effects of emission line lamps (and in particular the Ar lines), a common practice is to install two such lamps, with one used every night, and the other as master calibrator used only rarely (Quirrenbach et al., 2012).

### 2.3.4 Infrared calibration

One issue that has restricted high-accuracy radial velocities in the near-infrared has been the lack of a suitable wavelength calibrator. I<sub>2</sub> and Th–Ar lines used in the visible, for example, are sparse in the near infrared.

Infrared calibration using imprinted atmospheric lines reaches 10–20 m s<sup>-1</sup>. For the Kitt Peak McMath Fourier transform spectrometer, Deming et al. (1987) found variations of ~20 m s<sup>-1</sup> based on telluric CH<sub>4</sub>. For the  $R = 100\,000$  Nasmyth-mounted cryogenic échelle spectrograph CRILES at the VLT, designed for high-resolution spectroscopy between 0.96–5.2 μm, Seifahrt

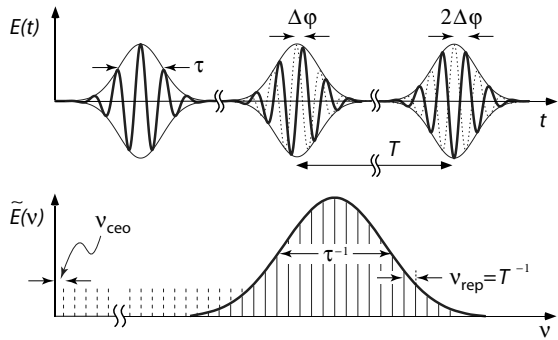


Figure 2.11: Principle of the laser frequency comb. A pulse train (top) produces the optical frequency ‘comb’ in Fourier space (bottom), with shorter pulse envelopes  $\tau$  producing broader frequency combs. Within the laser cavity, the round-trip pulse time,  $T$ , determines the repetition frequency,  $\nu_{rep} = 1/T$ . Dispersive elements cause a difference in the group and phase velocities, shifting the carrier wave with respect to the envelope by  $\Delta\phi$  per pulse. In the frequency domain, the comb shifts by  $\nu_{ceo} = \Delta\phi/2\pi T$ . From Murphy et al. (2007, Figure 1), © Oxford University Press.

& Käuffel (2008) reported telluric N<sub>2</sub>O lines near 4.1 μm stable to ~10–20 m s<sup>-1</sup>. Both studies used external N<sub>2</sub>O gas cells for wavelength calibration.

The development and optimisation of near-infrared gas cells is ongoing. Mahadevan & Ge (2009) concluded that H<sup>13</sup>C<sup>14</sup>N, <sup>12</sup>C<sub>2</sub>H<sub>2</sub>, <sup>12</sup>CO, and <sup>13</sup>CO together could provide useful calibration in the 1.65 μm H band. Valdivielso et al. (2010) describe a gas mixture (including C<sub>2</sub>H<sub>2</sub>, N<sub>2</sub>O, NH<sub>3</sub>, and various chloromethanes and hydrocarbons) with absorption lines spanning a wide region in the near infrared. Experiments using an NH<sub>3</sub> cell for VLT-CRILES in the 2.2 μm K band reached a precision of 3–5 m s<sup>-1</sup> over weeks or months (Bean et al., 2010b). Anglada-Escudé et al. (2012c) evaluated the use of CH<sub>4</sub> cells, and performed a comparison with the NH<sub>3</sub> cell adopted for VLT-CRILES.

For CARMENES (S2.6.5), U–Ne emission lamps are in use for the near-infrared arm.

### 2.3.5 Laser frequency combs

Gas cells and emission lamps depart somewhat from an ideal radial velocity standard. A more robust calibrator would cover the entire optical/infrared range with individually unresolved lines, of uniform spacing and intensity, and with accurately known wavelengths determined by fundamental physics. *Laser frequency combs*, or *astro combs*, generated from mode-locked femtosecond-pulsed lasers (Reichert et al., 1999; Jones et al., 2000a; Udem et al., 2002), offer this possibility (Figure 2.11).

The application of laser combs to spectrograph calibration for exoplanet detection, at ~0.01 m s<sup>-1</sup>, was evaluated by Murphy et al. (2007). A number of laboratory prototypes have subsequently been developed and

demonstrated (e.g. Osterman et al., 2007; Li et al., 2008a; Steinmetz et al., 2008; Schettino et al., 2010; Phillips et al., 2012a,b; Johnson et al., 2014a; Probst et al., 2015; Del’Haye et al., 2016; Kashiwagi et al., 2016; McCracken et al., 2017b; Xu et al., 2017a).

**Principles** Laser frequency combs rely on the storage of a single laser pulse, maintained on a repetitive path, and circulating in a cavity as a carrier wave. After each circuit, a copy of the pulse is emitted through an output mirror, resulting in an indefinite pulse train; the energy lost is replenished by stimulated emission in the lasing medium. Absolute line frequencies are

$$\nu = \nu_{\text{ceo}} + n \nu_{\text{rep}}, \quad (2.46)$$

where  $\nu_{\text{rep}} = 1/T$  is the laser repetition rate (with  $T$  being the round-trip travel time),  $\nu_{\text{ceo}}$  is a carrier-envelope offset frequency which must be calibrated (resulting from non-commensurability of the carrier-wave and repetition frequencies), and  $n$  is an integer, with modes given by  $n \sim 10^5 - 10^6$ . Both  $\nu_{\text{rep}}$  and  $\nu_{\text{ceo}}$  can be synchronised to atomic clocks.

Using GPS time referencing, the comb frequencies are expected to have long-term fractional stability and accuracy better than  $10^{-12}$ , corresponding to a velocity variation below  $0.01 \text{ m s}^{-1}$ . By providing a common absolute frequency standard, external time referencing should also allow the direct comparison of measurements made at different observatories.

In practice, various architectures are used to extend the wavelength coverage (including frequency doubling or spectral broadening), or to filter the dense mode spacing to one matched to the spectrograph resolving power, e.g. using a Fabry–Pérot étalon (McCracken et al., 2017a).

**Practical implementation** Early astronomical demonstrations/calibrations included use on the solar spectrograph at the Vacuum Tower Telescope (VTT, Tenerife Steinmetz et al., 2008). A laser frequency comb developed at CfA Harvard was used to calibrate the Whipple Observatory’s TRES spectrograph (Li et al., 2008a; Latham, 2008b). The prototype used a mode-locked titanium–sapphire laser operating at  $\sim 800 \text{ nm}$ , providing  $\nu_{\text{rep}} \sim 1 \text{ GHz}$ . A Fabry–Pérot cavity increased the intrinsic line spacing to a more usable  $40 \text{ GHz}$ . One comb was operated over a  $100 \text{ nm}$  band around  $800 \text{ nm}$ , and a second over a  $20 \text{ nm}$  band around  $400 \text{ nm}$ , yielding calibration and stability below  $1 \text{ m s}^{-1}$  (Phillips et al., 2012b). Subsequent deployment was made at HARPS–N (TNG, La Palma), where it is centred at  $550 \text{ nm}$  and generates 6000 lines equally spaced by  $0.015 \text{ nm}$  over a range of  $100 \text{ nm}$  (Li et al., 2012a).

A Yb fiber-fed laser comb was evaluated for HARPS in November 2010 and January 2011, and yielded calibration lines over  $450\text{--}590 \text{ nm}$  (Wilken et al., 2012). Applied to HD 75289, they demonstrated short-term repeatability of  $0.025 \text{ m s}^{-1}$  (Figure 2.12). Other laser combs have since been implemented and tested, or are planned, amongst them TNG–GLIANO (Schettino et al., 2011); VTT (Doerr et al., 2012); AAT–UHRF (Murphy et al., 2012); HET–Pathfinder (Ycas et al., 2012); Wendelstein–FOCES (Brucalassi et al., 2016a); NAO–Xinglon 2.16-m (Ye et al., 2016); and SALT–HRS (McCracken et al., 2017b).

Future challenges include broader wavelength coverage (e.g.  $0.37\text{--}2.5 \mu\text{m}$  for E-ELT–HIRES), as well issues of operational lifetime and automation (McCracken et al., 2017a).

### 2.3.6 Fabry–Pérot étalons

Fabry–Pérot interferometers or étalons also provide a quasi-periodic and dense grid of lines and homoge-

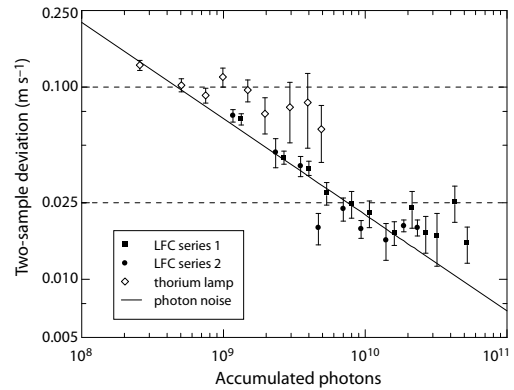


Figure 2.12: Calibration of the laser frequency comb for ESO–HARPS, showing the two-sample deviation of the two long calibration runs. The smallest number of accumulated photons,  $N$ , represents one acquisition, and several consecutive acquisitions can be added to obtain larger values of  $N$ . For  $N < 5 \times 10^9$ , the uncertainty decreases as  $N^{-0.5}$ , due to photon noise (solid line). For  $N > 5 \times 10^9$  there is no further reduction, which flattens at  $\sim 0.025 \text{ m s}^{-1}$  (lower dashed line). This represents the minimum calibration uncertainty achieved, and is reached after 4 min. The two-sample deviation of 116 Th lamp calibrations is also shown (open diamonds). One acquisition with the Th lamp has a much larger photon noise, and a minimum uncertainty of  $\sim 0.1 \text{ m s}^{-1}$ . Four data points of  $5 \times 10^9$  photons require 2 h. From Wilken et al. (2012, Figure 3), by permission from Nature/Springer/Macmillan Ltd, ©2012.

neous amplitudes, and can provide economical alternatives to the laser frequency comb (Bauer et al., 2015). Operated with a hollow-cathode lamp, they can map the lamp’s spectral features onto an absolute scale, for example calibrating large distortions (of some  $50 \text{ m s}^{-1}$ ) in the wavelength solution of the HARPS data reduction software, and yielding differences of  $\lesssim 10 \text{ m s}^{-1}$  with results from a laser frequency comb (Bauer et al., 2015).

They have been used or considered for various state-of-the-art instruments, including HARPS (Wildi et al., 2011), CARMENES (Schäfer & Reiners, 2012; Reiners et al., 2014), APOGEE and HPF (Halverson et al., 2014), and SPIRou (Cersullo et al., 2017). Actively stabilised étalons are also used (e.g. Halverson et al., 2014; Schwab et al., 2015), and high-accuracy ( $0.1 \text{ m s}^{-1}$ ) dual cavity systems have been considered (Banyal & Reiners, 2017).

### 2.3.7 Radial velocity standards

Verification of global error control is provided by continual monitoring of stars suspected to be true null standards, such as HD 185144 ( $\sigma \text{ Dra}$ ), a bright intrinsically quiet star with no discernible variations, or with simple, well-characterised planetary systems. These include (e.g. Vogt et al., 2014b) HD 168746 (with a 6.4-d Saturn-mass), HD 185269 (with an eccentric 6.8-d Jupiter), HD 187123 (with a 3.1-d hot Jupiter), and HD 209458 (with its 3.5-d hot Jupiter).

### 2.3.8 Fiber coupling

Various state-of-the-art instruments employ fiber feed to couple the telescope focus to the spectrograph. This offers two advantages. Firstly, it overcomes variable light illumination of the spectrograph slit, and the associated complications of wavelength calibration. This is because multiple internal reflections within the fiber cause scrambling of the image structure between input and output, decoupling the illumination of the spectrograph optics and detector from guiding errors and calibration source misalignments (Hubbard et al., 1979; Barden et al., 1981; Heacox & Connes, 1992; Heacox, 1986, 1988; Hunter & Ramsey, 1992; Connes et al., 1996; Walker et al., 2003b). In addition, the spectrograph can be distanced from the telescope, in a more mechanically and thermally stabilised environment, also minimising the effects of gravitational flexure.

Fiber-feed was first adopted for ELODIE at the OHP 1.9-m telescope (Baranne et al., 1996), and used for the detection of the first exoplanet discovered around a main sequence star, 51 Peg (Mayor & Queloz, 1995). The same concept has subsequently been used for HARPS, CARMENES, HPF and others. In CARMENES, for example, each (optical or near infrared) spectrograph is fed by two optical fibers with 100  $\mu\text{m}$  core diameter (1.5 arcsec on the sky), with one fiber carrying the starlight, and the second used for simultaneous emission line lamp calibration or sky subtraction (Quirrenbach et al., 2012). A core diameter of 300  $\mu\text{m}$  is used for HPF. These *multi-mode fibers* contrast with the *single-mode fibers*, for which a much smaller diameter core (typically 10  $\mu\text{m}$ ) allows only one mode of light to propagate (with a corresponding reduction in internal reflections and therefore reduced attenuation).

**Modal noise and fiber shaking** The 100–300  $\mu\text{m}$  core diameters in typical use imply the propagation of some  $10^2 - 10^4$  electromagnetic modes (Mahadevan et al., 2014a). This finite number of transmission modes introduces an error term in high-resolution spectra which cannot be eliminated by flat-fielding, because the measured intensity distribution is sensitive to small changes in fiber position or illumination. This *modal noise*, rather than photon shot noise, limits the achievable signal-to-noise ratio in fiber-fed spectrographs, to  $S/N \lesssim 500$  at  $R \sim 150000$  in the experiments of Baudrand & Walker (2001). They observed an (unexplained) empirical relation between the number of monochromatic modes and the level of modal noise, and found that continuous, low-amplitude agitation of the fiber eliminated the problem. Mechanical fiber agitation, or ‘shaking’, is now a standard component of fiber-fed systems (e.g. Sutherland et al., 2016). An alternative uses an integrating sphere with a diffuser that is moved rapidly using electrostrictive polymers (Mahadevan et al., 2014a).

**Scrambling and fiber cross section** Despite the intrinsic light-scrambling properties of optical fibers (Hunter & Ramsey, 1992; Avila et al., 1998; Avila & Singh, 2008) the illumination produced by a circular optical fiber still depends on how light is fed into the fiber, i.e. motion of the stellar image at the fiber en-

trance can produce a change in the illumination of the spectrograph, and hence mimic a radial velocity effect. Double scramblers were developed to provide further improvements (Hunter & Ramsey, 1992; Baranne et al., 1996).

Non-circular fibers, and specifically fibers with a square or octagonal cross section, can provide better scrambling as they lack the symmetry that leads to incomplete radial scrambling in circular fibers (Perruchot et al., 2011; Chazelas et al., 2012a; Plavchan et al., 2013a; Sutherland et al., 2016). Better performance with octagonal fibers has been demonstrated for both HARPS-N (Cosentino et al., 2012) and SOPHIE+ (Bouchy et al., 2013), resulting in an improvement from 5–6  $\text{m s}^{-1}$  for SOPHIE to around 1–2  $\text{m s}^{-1}$  for SOPHIE+. Use of octagonal fibers is now widespread, while D-shaped fibers offering ‘chaotic scrambling’ are also under development (Stürmer et al., 2016).

**Adaptive optics and photonic lanterns** Future instruments, notably for very large telescopes, are likely to benefit from the use of adaptive optics (to reduce the size of the seeing-limited stellar image) coupled to a *photonic lantern* (or photonic reformatter), which converts a multimode fiber input into a small number of single mode fiber outputs (Leon-Saval et al., 2010).

Such an approach, already proposed by Connes et al. (1996), offers prospects of reducing instrument size, allowing for more compact instrument designs with good optomechanical stability, while also eliminating modal noise (Ihle et al., 2010; Schwab et al., 2014; Feger et al., 2014; Crepp, 2014; Harris et al., 2016). The first such operational instrument is likely to be iLocater, under development for the  $2 \times 8.4\text{-m}$  LBT, and targeting operations in 2018 (Crepp et al., 2016).

## 2.4 Accuracy limits and error sources

Improvements in detector technology, wavelength calibration, and various other aspects of instrument design brought the state-of-the-art radial velocity accuracy to some 3–5  $\text{m s}^{-1}$  by the mid-1990s (e.g. Butler et al., 1996), and to around 0.3–0.5  $\text{m s}^{-1}$  today (Pepe & Lovis, 2008). Such accuracy represents a displacement of a few nm at the CCD detector, demanding a combination of optical and algorithmic techniques to maintain the required metrology over several years.

Although the radial velocity amplitude is independent of the distance to the star, signal-to-noise considerations limit observations to the brighter stars, typically  $V \lesssim 8 - 10$  mag. Equation 2.27 indicates that radial velocity measurements implicitly favour the detection of massive planets, those with small  $a$  (i.e. small  $P$ ) and, with adequate temporal sampling, large  $e$  (but see §2.1.2 for detectability in practice).

Error sources potentially imposing practical limits on achievable accuracy include instrumental errors, photon noise, and stellar ‘noise’, or stellar ‘jitter’ at various time scales and amplitudes (§2.4.5).

Other effects include spectral contamination (e.g. Pepe et al., 2004b; Pepe & Lovis, 2008; Cunha et al., 2013), including the contribution of micro-telluric lines, i.e. telluric lines that are not masked out for the radial velocity computation (Cunha et al., 2014), as well as contributions due to unrecognised planetary companions.

### 2.4.1 Photon noise

Achievable radial velocity accuracies scale with signal-to-noise. Estimates for ELODIE, and comparisons with real data, were detailed by Connes et al. (1996). For the HARPS instrument at the ESO 3.6-m telescope, a photon-limited precision of  $\sim 1 \text{ m s}^{-1}$  is reached for a  $V = 7.5 \text{ mag}$  G dwarf in around 60 s. In the absence of other noise sources, a single measurement accuracy of  $0.1 \text{ m s}^{-1}$  requires exposure times  $\gtrsim 100 \text{ min}$ . Photon-noise limits for CORALIE and HARPS are given by Bouchy et al. (2001).

### 2.4.2 Detection versus signal-to-noise

The signal-to-noise ratio at which a radial velocity survey can detect planets with a given period depends on the strength of the signal  $K$ , the magnitude of the measurement uncertainties  $\sigma$ , the survey duration  $T$ , and the total number of observations  $N$ . The time-dependent radial velocity of a star orbited by a planet on a circular orbit with period  $P$  has the form  $v(t) = K \sin(2\pi t/P - \phi_0)$ , where  $\phi_0$  is an arbitrary phase. For a uniform and continuous sampling of the radial velocity curve, such that observations at  $N$  epochs are taken over a survey duration  $T$ , each with a measurement uncertainty  $\sigma$ , then the detection S/N is

$$S/N(\phi_0) = \left\{ \frac{N}{\sigma^2} \frac{1}{T} \int_{-T/2}^{T/2} [v(t) - \langle v(t) \rangle]^2 dt \right\}^{\frac{1}{2}}, \quad (2.47)$$

where  $\langle v(t) \rangle$  is the time average of  $v(t)$  and is a function of  $\phi_0$ . Averaging over  $\phi_0$ , gives a ‘phase-averaged’ S/N for a radial velocity detection

$$\langle \text{SNR} \rangle_{\phi_0} = \left( \frac{N}{2} \right)^{\frac{1}{2}} \left( \frac{K}{\sigma} \right) \left\{ 1 - \frac{1}{\pi^2} \left( \frac{P}{T} \right)^2 \sin^2 \left( \frac{\pi T}{P} \right) \right\}^{\frac{1}{2}}. \quad (2.48)$$

For  $P/T \ll 1$ , the S/N for a detection is very nearly independent of period

$$\langle \text{SNR} \rangle_{\phi_0} \sim \left( \frac{N}{2} \right)^{\frac{1}{2}} \left( \frac{K}{\sigma} \right). \quad (2.49)$$

As expected, more epochs, improved measurement errors, and longer survey durations increase the detection S/N. Even for  $P \sim T$ , Equation 2.49 remains a good approximation. Although this assumes no detection dependence on eccentricity, in practice planets with  $e \geq 0.6$  are more difficult to detect (Cumming, 2004)

**Radial velocity fitting challenge** To establish further confidence in claimed detections given the various analysis methods used by different groups and based on different instruments, a ‘fitting challenge’ has evaluated the consequences of the use of different activity indicators, red-noise models, and a Bayesian analysis framework (Dumusque, 2016; Dumusque et al., 2017).

Results were formulated in terms of the ratio  $K/N = (K_{\text{pl}}/RV_{\text{rms}}) \sqrt{N_{\text{obs}}}$ , where  $K_{\text{pl}}$  is the semi-amplitude of each planetary signal,  $N_{\text{obs}}$  is the number of observation in each system, and  $RV_{\text{rms}}$  is the radial velocity rms of each system once the best-fit of a model (consisting of a linear correlation with  $\log(R'_{\text{HK}})$  plus a second-order polynomial as a function of time) was removed.

Their findings are that planets can be found down to  $K/N = 5$ , with a threshold of  $K/N = 7.5$  at the level of 80–90% recovery rate found for a number of methods. For  $K/N < 7.5$  recovery rates drop dramatically, while false positives increase, suggesting that  $K/N = 7.5$  provides an appropriate threshold for planet discovery.

### 2.4.3 Exposure metering

Starting with ELODIE (Baranne et al., 1996), many instruments including Keck–HIRES, the Lick Observatory Hamilton Spectrometer, and the Lick Automated Planet Finder (APF), employ an integral exposure meter to monitor ongoing exposures. This is used to optimise exposure times for a required signal-to-noise, and to calculate the photon-weighted midpoint of each exposure for barycentric correction (Kibrick et al., 2006).

HIRES, for example, uses a ‘propellor’ mirror behind the spectrometer slit to direct a few percent of the light to a dedicated photomultiplier. APF employs a semi-transparent ‘pellicle’ mirror, operating at 1 Hz, for auto-guiding, exposure metering, and barycentric weighting. A multiple-channel exposure meter for EXPRES at the Lowell 4.3-m Discovery Channel Telescope, designed to take account of chromatic atmospheric effects, is described by Blackman et al. (2017).

### 2.4.4 Instrument errors

Potential instrument-related error sources include the effects of mechanical and thermal stability, wavelength calibration (§2.3), spectrograph illumination (§2.3.8), and timing and coordinate systems (§2.2.4).

**Self-calibration versus simultaneous reference** Any instrumental effect that produces a distortion or a shift of the spectral line in the detector-pixel space will be interpreted, if not detected and recognised, as a wavelength change and thus a Doppler shift. Broadly, two methods of tracking changes in the instrumental profile changes have been used (Pepe et al., 2014a).

The first superimposes an absorption spectrum of a reference gas cell on the stellar spectrum, such that the instrument profile is continuously measured (§2.3.2). This *self-calibration technique* is particularly effective in spectrographs with varying instrument profiles, notably for slit spectrographs. Disadvantages are the restricted bandwidth of the gas-cell spectrum, the loss of efficiency due to absorption in the light path, and the need for a sophisticated deconvolution process to recover the stellar spectrum and thus the radial velocity.

Table 2.1: Estimated radial velocity jitter,  $\sigma'_{rv}$ , for various spectral types and luminosity classes.

Type	Jitter ( $\text{m s}^{-1}$ )	Comment	Reference
FV	7–30	$v_{\text{rot}} = 8 - 10 \text{ km s}^{-1}$	Saar et al. (1998)
"	2–7	inactive stars	Wright (2005)
GV	20–45	$v_{\text{rot}} = 8 - 10 \text{ km s}^{-1}$	Saar et al. (1998)
GKV	$4.6 \pm 1.8$	$v_{\text{rot}} \leq 2 \text{ km s}^{-1}$	Saar et al. (1998)
"	2–5	inactive stars	Wright (2005)
MV	2–7	inactive stars	Wright (2005)
GKIV	5–10	subgiants	Wright (2005)
KIII	20	giants	Hekker et al. (2006b)

The second method, the *simultaneous reference technique*, as employed for ELODIE, HARPS and others, assumes a stabilised instrumental profile that does not change between two wavelength calibrations of the spectrograph, such that the relationship between detector pixel and wavelength remains valid over time scales of typically one night. A second channel carrying a spectral reference is continuously fed to the spectrograph to monitor and correct for potential instrumental drifts or instrument profile changes. It is then essential that the changes that the scientific and the reference channels are subject to are identical over the time scale of one observing night. Therefore, the whole design of the instrument must be optimised for stability of the instrumental profile, demanding fiber feed and light scrambling, as well as pressure, mechanical, thermal and optical stability. The effort is compensated for by an unrestricted spectral bandwidth and the acquisition of an ‘uncontaminated’ scientific spectrum.

#### 2.4.5 Stellar activity

Activity in the stellar atmosphere (due to spots and/or plages), as well as stellar oscillations, and surface granulation, may all contribute astrophysical noise or ‘jitter’ to the radial velocity measurements, and become a prominent issue at the  $\text{m s}^{-1}$  level. These phenomena alter the shape of the stellar absorption lines by injecting spurious or systematic radial velocity signals that may mask or mimic planetary signals, and therefore complicate determination of the underlying centre-of-mass Keplerian motion. The effects are one of the dominant issues faced by future spectrographs targeting  $0.1 \text{ m s}^{-1}$  accuracies (e.g. Fischer et al., 2016a).

There are many examples of these effects reported in the literature, for example in the cases of HD 166435 (Queloz et al., 2001), HD 219542 (Desidera et al., 2003, 2004a), TW Hya (Huélamo et al., 2008), and BD+20 1790 (Figueira et al., 2010a).

Jitter due to inhomogeneities of the stellar atmosphere (spots, plages) is often significant, frequently imposes a limit to the accuracy of radial velocity measurements, and is expected to vary on time scales comparable to the stellar rotation period. It is correlated

with stellar chromospheric activity (e.g. Saar & Donahue, 1997; Saar et al., 1998; Butler & Marcy, 1998; Saar & Cuntz, 2001; Tinney et al., 2002b; Shkolnik et al., 2005; Jenkins et al., 2006; Desort et al., 2007; Saar, 2009). Emission in the core of the Ca H/K lines is a useful proxy, although active stars seen pole-on can have a high activity index but low radial velocity jitter.

The effects of stellar oscillations on Doppler measurements are typically smaller than those produced by activity, and are most significant for giants and subgiants. O’Toole et al. (2008) made an analysis using data from asteroseismological investigations using AAT-UCLES. They found a power-law relation between measured noise and both the luminosity-to-mass ratio of the target stars and integration times (Figure 2.13), showing that it is advantageous to average over several p-mode oscillation frequencies (O’Toole et al., 2009b). HARPS results have also shown that 15-min integrations are sufficient to damp resulting radial velocity variations to below  $0.2 \text{ m s}^{-1}$  (Udry & Mayor, 2008).

Surface granulation can induce variability of order  $1 \text{ m s}^{-1}$  for solar type stars (Kjeldsen et al., 2005), which may demand measurements over several hours to damp.

The overall effects of jitter can be characterised as an excess in the radial velocity standard error as (Saar et al., 1998; Wright, 2005)

$$\sigma'_{rv} = (\sigma_{rv}^2 - \sigma_{\text{meas}}^2)^{1/2}, \quad (2.50)$$

where  $\sigma_{\text{meas}}$  is the contribution of the measurement error to the radial velocity standard error,  $\sigma_{rv}$ , for a given star, and  $\sigma'_{rv}$  includes contributions from all of the effects noted above.

Astrophysical contributions are dependent on a number of variables, including stellar rotational velocity and age; some indicative estimates are given in Table 2.1 and Figure 2.14. The activity–rotation–age relationship for solar-type stars also applies to early M dwarfs (e.g. Maldonado et al., 2017; Scandariato et al., 2017).

Various recent models of the resulting contributions to radial velocity time series have been developed (e.g. Korhonen et al., 2015; Rajpaul et al., 2015; Gregory, 2016; Herrero et al., 2016), including specific models for M dwarfs (Andersen & Korhonen, 2015).

**Summary for GK dwarfs** For GK dwarfs, stellar signals relevant at  $\sim 1 \text{ m s}^{-1}$  can be decomposed in four components (Dumusque et al., 2017):

- (a) solar-type oscillations (e.g. Kjeldsen et al., 2005; Arntoft et al., 2008; O’Toole et al., 2008; Dumusque et al., 2011a);
- (b) granulation phenomena (e.g. Dravins, 1982; Lindgren & Dravins, 2003; Del Moro, 2004; Del Moro et al., 2004; Dumusque et al., 2011a; Gray & Oostra, 2018).
- (c) short-term activity signals on the stellar rotation period time scale (e.g. Saar & Donahue, 1997; Saar, 2009;



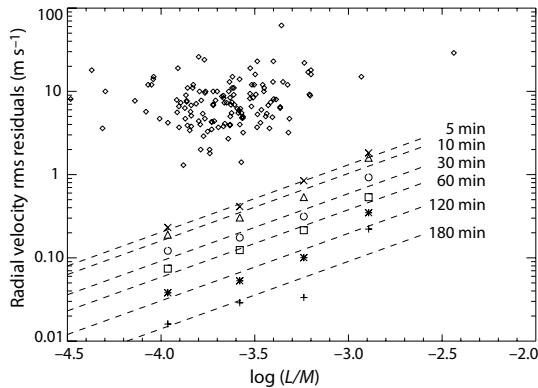


Figure 2.13: Oscillation jitter of AAT-UCLES asteroseismology targets as a function of  $\log_{10}(L/M)$  (luminosity–mass ratio) for various simulated integration times. Power laws derived by O’Toole et al. (2008, their eqn 2) are shown as dashed lines. Residual rms values for the sample of known planets from Butler et al. (2006b) are shown as small diamonds. From O’Toole et al. (2008, Figure 4), © Oxford University Press.

Meunier et al., 2010a; Boisse et al., 2012a; Robertson et al., 2014; Borgniet et al., 2015; Robertson et al., 2015a; Haywood et al., 2016);

(d) long-term activity signals on the magnetic cycle period time scale (e.g. Makarov, 2010; Dumusque et al., 2011c; Meunier & Lagrange, 2013a; Díaz et al., 2016b; Lanza et al., 2016).

**Treatment** Regarding short-term stellar activity, the most difficult signals to treat are non-periodic stochastic terms arising from the evolution and decay of active regions. Numerous correction techniques have been investigated (Dumusque et al., 2017): • fitting sine wave and harmonics at the rotation period of the star (Boisse et al., 2011); • use of red-noise models (Gregory, 2011b; Tuomi et al., 2013a; Feroz & Hobson, 2014); • exploiting contemporaneous photometry (Aigrain et al., 2012; Haywood et al., 2014b; Dumusque et al., 2015a); • modeling activity-induced signals with Gaussian process regression, whose covariance properties are shared either with the stellar photometric variations (Haywood et al., 2014b; Grunblatt et al., 2015), or a combination of several spectroscopic indicators (Rajpaul et al., 2015), or determined from the radial velocities themselves (Faria et al., 2016a); • using linear correlations between the different observables, i.e., radial velocity, bisector span, and width of the cross correlation function (Baranne et al., 1996; Pepe et al., 2002), photometry (Queloz et al., 2001; Boisse et al., 2009; Robertson et al., 2014, 2015a), and magnetic field strength (Hébrard et al., 2014a); • checking for season per season phase incoherence of signals (Dumusque et al., 2012, 2014a; Santos et al., 2014); and • avoiding the impact of activity by using wavelength-dependent criteria (Anglada-Escudé & Butler, 2012; Tuomi et al., 2013a).

**Earth-mass planets in the habitable zone** The sun spot and plage properties of the Sun over one solar cycle, between 1993–2003, have been used to infer the radial velocity curve of a solar-type star exhibiting such features (Lagrange et al., 2010b; Meunier et al., 2010a). The radial velocity amplitude varies, in a complex way, from a few tenths up to  $\sim 5 \text{ m s}^{-1}$ . Assuming radial velocity accuracies in the range  $0.01\text{--}0.1 \text{ m s}^{-1}$  for a Sun-

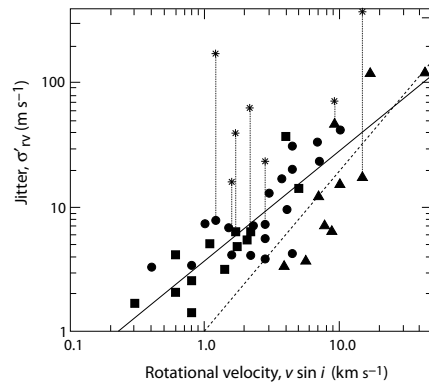


Figure 2.14: Early results from the Lick survey, showing the dependency of astrophysical jitter,  $\sigma'_{rv}$  (Equation 2.50) on stellar rotational velocity,  $v \sin i$  for main sequence stars, indicated as F (triangles), G (circles) and K (squares). Stars with planets are plotted before (asterisks) and after (connected by vertical dashed lines) accounting for the planet’s contribution. The power-law fits have exponent 0.9 for G and K stars (solid line), and 1.3 for F stars (dashed). From Saar et al. (1998, Figure 2a), by permission of IOP Publishing/AAS.

like star at 10 pc, detection of a  $1M_{\oplus}$  planet in the habitable zone, between 0.8–1.2 au, would require weekly sampling over several years, with frequent temporal sampling being crucial. Variations in the Sun’s total solar irradiance during cycle 23, as measured by SOHO-VIRGO, is reported by Lanza et al. (2003).

**Activity indicators** Chromospheric activity indicators include Ca II H and K, H $\alpha$ , He I D3, and Na I D1 and D2 (Figure 2.15). The frequently used Mt. Wilson S-value scale is defined as the ratio of the sum of the flux in the cores of the Ca II H and K lines to the sum of two continuum bands, redward and blueward of the H and K lines (Wilson, 1968). In the near-infrared, the Ca II triplet provides a proxy (Robertson et al., 2016).

The  $R'_{HK}$  index is derived from the S-value by converting into a standard scale and correcting for the residual photospheric emission, leading to a non-dimensional measure of chromospheric emission. This effectively removes any dependencies on the bolometric flux, allowing accurate comparison of the chromospheric emission across different spectral types (e.g. Knutson et al., 2010; Isaacson & Fischer, 2010; Astudillo-Defru et al., 2017a; Suárez Mascareño et al., 2017c).

**Detailed studies** Many detailed studies of the origin and effects of stellar noise on radial velocity measurements have been reported, including for M dwarfs (e.g. Saar & Fischer, 2000; Santos et al., 2000c; Narayan et al., 2005; Wright, 2005; Reiners, 2009; Santos et al., 2010a; Martínez-Arnáiz et al., 2010; Lagrange et al., 2011; Dumusque et al., 2011c,b; Boisse et al., 2011; Lanza et al., 2011a; Barnes et al., 2011a; Gomes da Silva et al., 2011, 2012; Boisse et al., 2012a; Aigrain et al., 2012; Cegla et al., 2012, 2014; Bastien et al., 2014b; Barnes et al., 2014; Astudillo-Defru et al., 2017a).

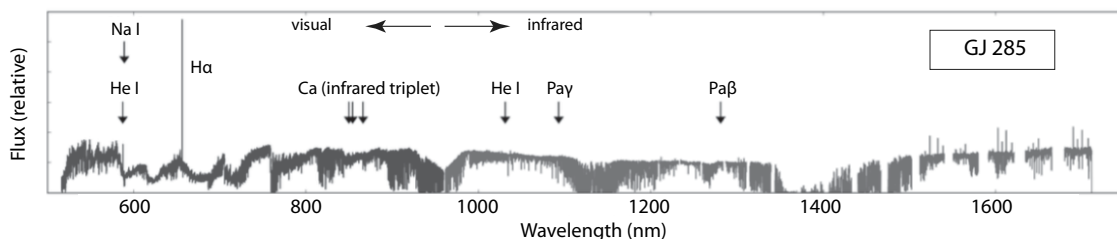


Figure 2.15: Optical-infrared spectrum of the M4.5V dwarf GJ 285 observed with CARMENES. Chromospherically sensitive lines (indicated) are distributed across the spectrum. In the optical, the  $H\alpha$  line is particularly prominent and several molecular band heads can be distinguished. The infrared spectrum shows the atmospheric J- and H-band ‘windows’ around 1.2–1.6  $\mu\text{m}$ , with a number of prominent airglow emission lines beyond 1.5  $\mu\text{m}$ . From (Quirrenbach et al., 2016, Figure 4), with permission ©SPIE.

**The Sun as a template** Monitoring of the Sun has also been used to characterise solar-type stellar activity and its impact on exoplanet detectability (e.g. Lagrange et al., 2010b; Meunier et al., 2010a; Lagrange et al., 2011; Meunier & Lagrange, 2013a,b; Borgniet et al., 2015; Marchwinski et al., 2015; Meunier et al., 2015; Haywood et al., 2016). The Sun’s radial velocity signal is also measurable in reflected light from minor bodies of the solar system, including the Moon, the Galilean satellites, and several asteroids, providing further insight into the relation between radial velocity and stellar activity (Lanza & Molaro, 2015; Lanza et al., 2016).

A dedicated solar telescope feeding the HARPS-N spectrograph (equipped with a laser frequency comb) is being used for intensive long-term monitoring of the Sun, and currently reaches weekly rms noise levels of  $0.6 \text{ m s}^{-1}$  (Dumusque et al., 2015a).

**Accounting for stellar jitter** Star spots and plages can induce radial velocity signals of  $1\text{--}100 \text{ m s}^{-1}$  (Saar & Donahue, 1997). There have been many attempts to remove this large-scale jitter, including the use of observational strategies, spot simulations, Keplerian models, bisector analysis, harmonic decomposition, Fourier component analysis/pre-whitening, and principal component analysis (Saar & Donahue, 1997; Hatzes, 2002; Desort et al., 2007; Melo et al., 2007; Bonfils et al., 2007; Boisse et al., 2009; Hatzes et al., 2010; Dumusque et al., 2011c; Boisse et al., 2011; Hatzes, 2013b; Gettel et al., 2013; Hatzes, 2013b; Moulds et al., 2013; Petit et al., 2015; Robertson et al., 2015a; Vanderburg et al., 2016d; Barnes et al., 2017; Davis et al., 2017).

Notwithstanding these removal techniques, active stars are still not ideal candidates for radial velocity follow-up and are thus often left out of planet surveys.

Even ‘quiet’ stars (those with little or no activity) exhibit jitter due to granulation and stellar oscillations, which can introduce radial velocity signals of  $1 \text{ m s}^{-1}$  or more (e.g. Schrijver & Zwaan, 2000). Observing strategies can be adapted to average out this small-scale jitter (Pepe et al., 2011; Dumusque et al., 2011c).

**Correlation with stellar rotation** Active areas moving across the stellar limb can lead to detection bias at the stellar rotation period, a specific problem if the planet is tidally-locked close to co-rotation (e.g. Petit et al., 2015; Vanderburg et al., 2016d).

**Correlation with magnetic cycles** From long-term monitoring, Santos et al. (2010a) found that the stellar activity indicators Ca II,  $H\alpha$ , and He I trace the magnetic cycle in solar type stars, as do the different parameters of the spectroscopic cross-correlation function such as the bisector and full width half maximum. At least for early K dwarfs, radial velocity amplitudes are perturbed by  $\lesssim 1 \text{ m s}^{-1}$  over the magnetic cycle.

For GJ 328 observed over 10 yr, the long-period magnetic activity cycle introduces an additional signal in the stellar radial velocity curve of amplitude  $6\text{--}10 \text{ m s}^{-1}$  (Robertson et al., 2013).

**Algorithmic implementation** Routines for the computation of photometry and radial velocity terms induced by star spots include SOAP (Boisse et al., 2012a) and SOAP 2.0 (Dumusque et al., 2014a).

#### 2.4.6 Excluding other sources of periodicity

Effects other than an orbiting exoplanet can result in periodic stellar radial velocity variations, including most of the noise terms considered in the previous section.

**Star effects** Surface activity such as spots and plages, as well as inhomogeneous convection, can lead to periodic radial velocity variations: a spot with a filling factor of a few percent can induce a radial velocity amplitude of a few  $\text{m s}^{-1}$  (Saar & Donahue, 1997). Activity may be discounted if the radial velocity period is distinct from the stellar rotation period, or if the star shows only very low level photometric variability at the radial velocity period (although spots are a time-dependent phenomenon). Spectroscopic measurements of the Ca II H and K lines provide a proxy for surface (magnetic) activity (Baliunas et al., 1995), and may reveal rotational

modulation attributable to stellar rotation. For close-in planets, magnetic interactions may cause additional stellar activity, as in CoRoT-7 (Lanza et al., 2010).

Stellar pulsations may also cause radial velocity variations, but tend to be discounted if their period and amplitude do not correspond to known excitation mechanisms for the relevant spectral type.

**Binary companions** Stellar companions can mimic exoplanet signatures, and can be difficult to rule out (see, e.g., HD 41004: Santos et al., 2002b; Zucker et al., 2003, 2004). Hipparcos catalogue astrometry, both the double star annex and the goodness-of-fit statistics for the single-star model (catalogue fields H29–H30), provides a first level of discrimination.

The presence of a lower-level stellar spectrum can also be investigated using TODCOR, a cross-correlation algorithm developed to detect and measure radial velocities of two components of a spectroscopic binary (Mazeh & Zucker, 1994). Its application to HD 41004 is described by Zucker et al. (2003). An extension to triple stellar systems TRICOR/TRIMOR is described, and applied to HD 188753, by Mazeh et al. (2009b).

A particularly confusing configuration may arise when a tight binary system orbits the target star. Schneider & Cabrera (2006) suggested that the binary wobble around its own centre of mass can result in the same modulation of the three basic observables (radial velocity, astrometric position, and time of arrival of a periodic signal) as for an orbiting planet. A more detailed analysis by Morais & Correia (2008) showed that the binary actually mimics two planets, rather than a single orbiting planet, but with very similar orbital periods.

**Period aliases** In radial velocity work, as in other areas of astronomy, observation sequences are frequently interrupted by semi-regular natural phenomena including the diurnal and lunar cycles, resulting in aliases due to stroboscopic effects.

Baluev (2012) examined the problem of distinguishing between two possible models, specifically for period alias ambiguities. Considering the statistical problem of selecting the best-fitting model (and as an alternative to the computationally-intensive Bayesian approach), he argued that the (non-Bayesian) *Vuong test* (Vuong, 1989) performs particularly well, and applied it to 55 Cnc, GJ 876, GJ 3634, HD 75898, and HD 156668.

**Retracted discoveries** Various retracted discoveries serve as illustrations of the complexities of orbit fitting in practice:

MARVELS-1 (TYC 1240-945-1) was reported as a  $28M_J$  companion in a  $P = 5.9$  d,  $e \sim 0$  orbit (Lee et al., 2011b); further radial velocities, imaging data, and bisector analysis, subsequently reclassified it as a face-on stellar binary in a hierarchical 3–4 star system (Wright et al., 2013).

HIP 11952 was reported as a 2-planet system from FEROS (Setiawan et al., 2012). Unconfirmed by HARPS (Desidera et al., 2013), re-analysis of the FEROS data attributed the claim to an error in barycentric correction (Müller et al., 2013a).

HD 41248 was reported as a 2-planet system in a possible

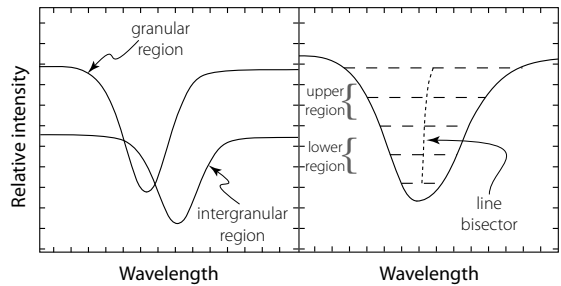


Figure 2.16: Schematic of line profile asymmetry caused by convection, and the resulting line bisector. Left: line profiles resolving individual convection cells would show blueshifted lines from the upflow regions, with redshifted lines from the intergranular downflow lanes. Right: the resulting line profile at low spatial resolution, with a consequently asymmetric line bisector. Adapted from Dravins et al. (1981, Figure 1), reproduced with permission © ESO.

7:5 resonance (Jenkins et al., 2013c), but subsequently attributed to stellar activity (Santos et al., 2014).

#### 2.4.7 Bisector analysis

The *spectral line bisector* is the locus of median points midway between equal intensities on either side of a spectral line, thereby dividing it into two halves of equal equivalent width (Figure 2.16). Line bisectors are used to quantify stellar line profile asymmetries, and are important in identifying the underlying cause of certain types of radial velocity variation.

Since the work of Voigt (1956), line bisectors have been used to describe the nature and strength of convection in the Sun, and in stellar photospheres on the cool side of the granulation boundary where deep convective motion is significant (Dravins, 1975; Dravins et al., 1981; Gray, 1982, 1983; Nowak & Niedzielski, 2008). In such photospheres, local upward motion in the brighter (hotter) convective cells is balanced by a downflow in the darker (cooler) intergranular lanes. In the absence of spatial resolution, averaging over many granules, an overall convective blueshift, of order  $-0.5 \text{ km s}^{-1}$ , results from the dominant contribution of blueshifted photons originating from the larger and brighter granules.

Bisectors due to solar-like granulation are shaped like a distorted ‘C’, and like the top-half of the letter ‘C’ for stars somewhat hotter or more luminous than the Sun. They show reversed curvature on the hot side of the granulation boundary, due to the structure of the surface convection zone (Gray, 1989; Gray et al., 2008).

**Bisector metrics** The shape of the spectral line bisector can be quantified in various ways: (a) the *bisector velocity span* (or 7% span) is constructed as the difference in bisector velocity between upper and lower regions of the line (Figure 2.16), avoiding the wings and cores (Toner & Gray, 1988; Hatzes, 1996; Queloz et al., 2001); (b) the *bisector inverse slope* (Queloz et al., 2001; Santos et al., 2002b) is  $v_t - v_b$ , where  $v_t$  is the mean bisector velocity between 10–40% of the line depth (top), and  $v_b$  is

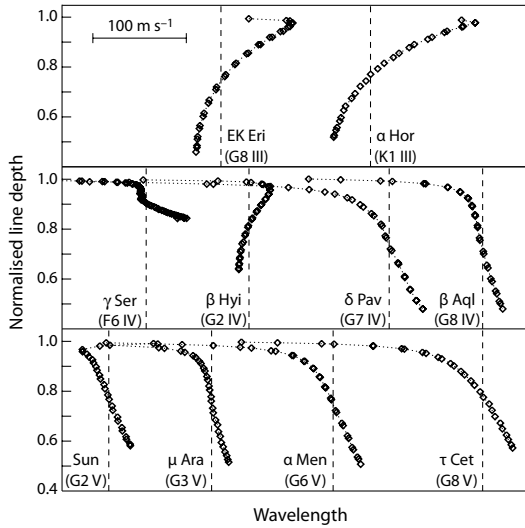


Figure 2.17: Mean bisectors, constructed from the cross-correlation function, of various bright stars according to luminosity class, III (top row) to V (bottom). Vertical dashed lines indicate the radial velocity. Error bars are the size of the plot symbols or smaller. From Dall et al. (2006, Figure 2), reproduced with permission © ESO.

that between 55–90% (bottom); (c) the *bisector curvature* is the difference in velocity span between the upper and lower halves of the bisector (e.g. Hatzes, 1996; Nowak & Niedzielski, 2008), for example  $(v_3 - v_2) - (v_2 - v_1)$ , where  $v_1, v_2, v_3$  are mean velocities at 20–30%, 40–55%, and 75–100% of the line depth (Dall et al., 2006). Various other forms are also used (e.g. Dall et al., 2006; Baştürk et al., 2011; Figueira et al., 2013).

Bisector analysis is usually made directly on the mean line profile given by the cross-correlation function, and used as an aid to distinguish planetary signatures from other types of radial velocity modulation (Povich et al., 2001; Martínez Fiorenzano et al., 2005). For a planetary signal, the bisector span is expected to be independent of radial velocity, whereas a distinct correlation arises for blended systems (e.g. for HD 41004: Santos et al., 2002b, Figure 3), or for periodic variations due to star spots (e.g. for HD 166435: Queloz et al., 2001, Figure 7).

As one of many examples, Dall et al. (2006) used HARPS observations of bright stars, both active and inactive, to derive the mean bisectors from individual lines, as well as from the cross-correlation function (Figure 2.17). They showed that different spectral lines can show different bisector shapes, even between lines of the same element, calling for caution in deriving global stellar properties from the bisector derived from the cross-correlation function alone.

## 2.5 Higher-order radial velocity effects

### 2.5.1 Gravitational redshift variations

The first-order effect of gravitational redshift is described in Section 2.2.4. Fluctuations in stellar radius would lead to variations in an escaping photon’s gravitational redshift, introducing noise into radial velocity measurements by shifting the *centroid* of the observed

spectral lines. The effect is in contrast with other types of stellar jitter which result in line asymmetries (Cegla et al., 2012). From the velocity shift for a photon detected at large distance from the stellar surface (Equation 2.44), a radius change of  $\delta R_\star$  would result (at constant mass) in a velocity variation  $\delta v_r = (\delta R_\star / R_\star) v_r$ .

**Solar radius variations** For the Sun,  $v_r = 636 \text{ m s}^{-1}$ , such that  $\delta R_\odot \sim 0.01\%$  would result in  $\delta \lambda \sim 0.06 \text{ m s}^{-1}$ . Since the radial velocity signal due to the Earth orbiting the Sun is  $\sim 0.09 \text{ m s}^{-1}$ , a radius change in a host star of  $\geq 0.01\%$  could mimic, or mask, the radial velocity signal of an Earth-like planet.

Cegla et al. (2012) tabulate various recent estimates of solar radius *variations* (see also §12.1.7). While some studies report solar radius changes of 0.01% or more observed from ground (e.g. Penna et al., 2010, and references), space-based observations from SOHO–MDI suggest that  $R_\odot$  is stable to  $\sim 10^{-6}$  (Bush et al., 2010).

**Stellar radius variations** In addition to the widely-observed pulsation-driven variations, a number of other mechanisms may give rise to stellar radius variations. Cegla et al. (2012) assessed the effects of the Applegate mechanism (box, page 114), magnetic-field induced convective inhibition, and the Wilson depression of star spots (§4.4.3). They found that the latter two could induce gravitational redshift variations up to  $0.04 \text{ m s}^{-1}$  and  $0.03 \text{ m s}^{-1}$  respectively (Figure 2.18). They suggest that for transiting systems, transit duration variations could allow changes in stellar radius to be monitored and perhaps corrected.

### 2.5.2 Zeeman effect

Models of activity-induced radial velocity variations (§2.4.5) typically focus on the impact of temperature contrast in spots, according to which the effects should diminish toward longer wavelengths. The *Zeeman effect* (splitting of a spectral line into several components in the presence of a static magnetic field) also has an effect on radial velocity measurements, but in the opposite sense: its relative importance should grow with wavelength because the Zeeman displacement itself grows with  $\lambda$ , and because a magnetic and cool spot contributes more to the total flux at longer wavelengths.

Reiners et al. (2013) modeled the effects of active regions, including both temperature contrast in spots and Zeeman broadening, calculating stellar line profiles using polarised radiative transfer models including atomic and molecular Zeeman splitting over the range  $0.5\text{--}2.3 \mu\text{m}$ . The amplitude of the radial velocity signal caused by the Zeeman effect can be comparable to that caused by temperature contrast; a spot magnetic field of 0.1 T can produce a similar radial velocity amplitude as a spot temperature contrast of 1000 K.

Table 2.2: Estimates of the tidal velocity amplitude for the 17 systems (from all known in 2012) with  $K_{\text{tide}} > 1 \text{ m s}^{-1}$ , as determined by Arras et al. (2012, Table 1). For the eccentric orbit cases, the  $k = 2$  orbital velocity amplitude,  $eK_{\text{orb}}$ , is given for comparison. NT under inclination indicates the planet is non-transiting.

Planet	$M_{\text{p}} \sin i$ ( $M_{\text{J}}$ )	$P_{\text{orb}}$ (d)	$e$	$\omega$ ( $^{\circ}$ )	$i$ ( $^{\circ}$ )	$M_{\star}$ ( $M_{\odot}$ )	$R_{\star}$ ( $R_{\odot}$ )	$K_{\text{tide}}$ ( $\text{m s}^{-1}$ )	$eK_{\text{orb}}$ ( $\text{m s}^{-1}$ )
CoRoT-14 b	7.6	1.51			79.6	1.13	1.21	4.1	
HAT-P-2 b	8.7	5.63	0.517	185	90.0	1.36	1.64	5.0	483
HAT-P-7 b	1.8	2.20			84.1	1.47	1.84	1.0	
HAT-P-23 b	2.1	1.21	0.106	118	85.1	1.13	1.20	3.6	39
HD 41004 B b	18.4	1.33	0.081	178	NT	0.40	0.48	3.6	517
HIP 13044 b	1.3	16.20	0.250	219	NT	0.80	6.70	2.7	30
OGLE-TR-56 b	1.3	1.21			78.8	1.17	1.32	2.1	
OGLE2-TR-L9 b	4.3	2.49			79.8	1.52	1.53	1.9	
SWEEPS-11	9.7	1.80			84.0	1.10	1.45	7.0	
WASP-4 b	1.1	1.34			88.8	0.93	1.15	1.1	
WASP-12 b	1.4	1.09			86.0	1.35	1.60	4.8	
WASP-14 b	7.7	2.24	0.090	255	84.8	1.32	1.30	1.6	91
WASP-18 b	10.1	0.94	0.009	-92	86.6	1.24	1.36	31.9	15
WASP-19 b	1.2	0.79	0.005	3	79.4	0.97	0.99	2.8	1
WASP-33 b	4.6	1.22	0.174	-89	87.7	1.50	1.44	5.9	120
WASP-43 b	1.8	0.81			82.6	0.58	0.93	8.9	
XO-3 b	11.8	3.19	0.260	346	84.2	1.21	1.38	3.1	385

### 2.5.3 Planet-induced tides

Close-in massive exoplanets raise significant tides in their stellar hosts (§10.11.2). Arras et al. (2012) computed the radial velocity signal due to this fluid motion in the ‘equilibrium tide approximation’, in which the fluid motion is incompressible and follows gravitational equipotentials (§10.11.6).

In the particular case of a circular orbit, the general expression for the tidal amplitude simplifies to (Arras et al., 2012, eqn. 15)

$$\begin{aligned} v_{\text{tide}} &= \frac{3}{2} n R_{\star} \frac{M_{\text{p}}}{M_{\star}} \left( \frac{R_{\star}}{a} \right)^3 f_2 \sin^2 \theta_0 \sin [2(nt - \phi_0)] \\ &\simeq 1.13 \text{ m s}^{-1} \left( \frac{M_{\text{p}}}{M_{\text{J}}} \right) \left( \frac{M_{\odot}^2}{M_{\star} (M_{\star} + M_{\text{p}})} \right) \end{aligned} \quad (2.51)$$

$$\times \left( \frac{R_{\star}}{R_{\odot}} \right)^4 \left( \frac{1 \text{ d}}{P_{\text{orb}}} \right)^3 \sin^2 \theta_0 \sin [2(nt - \phi_0)], \quad (2.52)$$

where  $n$  is the orbital frequency,  $\theta_0$  and  $\phi_0$  are defined in terms of the star–planet–observer coordinates, and  $f_2$  contains information on the limb darkening (the second numerical expression uses Eddington limb darkening with  $f_2 \simeq 1.1$ ). The tidal velocity term is largest for massive short-period planets around stars with large radii.

Their study shows that the orbital and tidally-induced radial velocity terms are distinct in phase for large eccentricities. For more circular orbits, and because both the tidal fluid flow and the epicyclic motion of a slightly eccentric orbit produce a radial velocity signature at twice the orbital frequency, the tidally-induced term can mimic a finite orbital eccentric.

The 17 systems for which tidal contributions are predicted to exceed  $1 \text{ m s}^{-1}$  are given in Table 2.2, the largest

being  $\sim 30 \text{ m s}^{-1}$  for WASP-18 b. Interestingly, the WASP-18 planet has a small but finite  $e = 0.007 - 0.009$  (Hellier et al., 2009a; TriAUD et al., 2010; Miller et al., 2012; Knutson et al., 2014c), and a pericentre longitude  $\omega \sim \pi/2$ , implying a coincidental orbit alignment with the line-of-sight. That this result is explained, in phase and amplitude, by the tidal velocity signature of an  $e = 0$  orbit, suggests that the reported eccentricity is a signature of the tidally induced radial velocity in the stellar host.

As a corollary, the measurement of both the orbital and tidal velocities for non-transiting planets may allow planet mass and inclination to be separately determined solely from radial velocity data.

### 2.5.4 Planet radial velocity signals

In almost all discussions of exoplanet radial velocities to date, information on the exoplanet orbit is (indirectly) derived from spectroscopy of (and therefore motion of) the host star, and any possible contributory signal from the planet itself is either irrelevant or ignored. Radial velocity measurements accordingly only yield a value of the *mass function* (§2.1.2), with the consequence that (in the absence of further constraints) the planet mass remains uncertainty by the unknown factor  $\sin i$ .

Direct measurement of the *planet’s* radial velocity, in addition to the star’s barycentric motion, would eliminate the  $\sin i$  uncertainty in the orbital orientation, and provide the planet’s true mass (and orbit inclination) directly, even for non-transiting system (§2.1.2).

In principle, such measurements could be made through high-resolution spectroscopy of the light from the host star *reflected* by the planet, or from the (infrared) thermal *emission* of the planet itself. As detailed

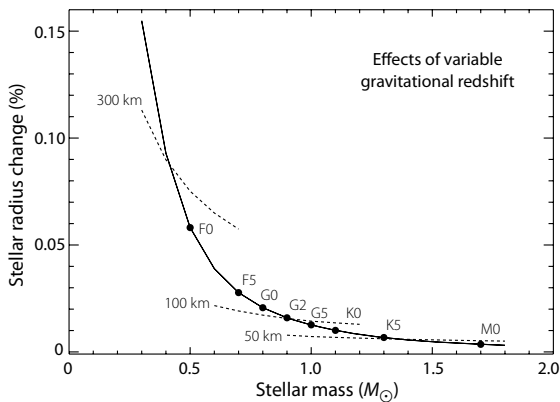


Figure 2.18: The effects of variable gravitational redshift due to a change in stellar radius. The solid curve shows the percentage change in stellar radius required to induce a  $\delta V_{\text{grav}}$  equivalent to an Earth-twin radial velocity signal. Solid circles indicate specific spectral types. Dashed curves represent stellar radius variations of 50, 100 and 300 km. From Cegla et al. (2012, Figure 1), © Oxford University Press.

in Chapter 6, such thermal emission has been detected for several transiting planets, either from Spitzer or low-resolution infrared spectroscopy from ground.

Ground-based high-resolution spectroscopy of the reflected or emitted light from the planet is particularly challenging because of the very low planet/star flux ratio ( $\sim 10^{-4}$  in the K-band), combined with contamination due to the Earth's atmospheric (telluric) absorption. The method is rendered feasible because the planet signal, unlike that of the telluric lines, is subject to a changing Doppler shift arising from the changing radial component of the planet's orbital velocity (some 100–150  $\text{km s}^{-1}$  for hot Jupiters). The telluric absorption can therefore be removed while preserving the planet signal, which is then analysed by cross correlation with a range of model planet atmosphere spectra.

**Observational results: infrared** Since 2012, a small number of planets have been detected at high spectral resolution in the near infrared, notably using VLT-CRIRES, resulting in direct signatures of the planet's orbital motion (Table 2.3).

*$\tau$  Boo*: the first exoplanet measured in this way,  $\tau$  Boo b, had previously been subject to several attempts to measure its orbit inclination through reflected light, without (convincing) success (§6.15.1). Brogi et al. (2012b) reported the detection of CO absorption in the thermal day-side spectrum of  $\tau$  Boo b, from VLT-CRIRES observations (in 2011 April). At  $R \sim 100\,000$ , they could trace the planet's radial velocity over a large range in phase, yielding  $M_{\text{p}} = 5.95 \pm 0.28 M_{\text{J}}$  and  $i = 44.5 \pm 1.5^\circ$ , thus confirming the planetary (mass) nature of the companion, and demonstrating that atmospheric characterisation is also possible for non-transiting planets. Similar obser-

**Relevance of carbon monoxide:** CO exhibits a dense sequence of deep absorption lines at around  $2.3 \mu\text{m}$ . Models predict CO to be one of the most abundant molecules in hot gas giants (Cooper & Showman, 2006; Sharp & Burrows, 2007). The possible detection of CO in the atmosphere of some transiting hot Jupiters has been reported (§11.6.2), mostly from low-resolution ( $R < 40$ ) HST-NICMOS near-infrared spectra or broad Spitzer photometry between  $3.6\text{--}24 \mu\text{m}$ , either via transmission (primary transit) and emission (secondary eclipse) observations.

Snellen et al. (2010a) detected CO in the transmission spectrum of HD 209458 b using  $2.30\text{--}2.33 \mu\text{m}$  high-resolution spectroscopy, providing the first direct measurement of the radial velocity of a transiting hot Jupiter. Brogi et al. (2012b) and Rodler et al. (2012) reported the first detection of an atmospheric chemical species, and associated radial velocity shift, for a *non-transiting* planet.

Strong CO *absorption* indicates an atmosphere with decreasing temperature towards higher altitudes. This is in contrast to the temperature inversion surmised for some other highly irradiated planets (Burrows et al., 2008a; Fortney et al., 2008a), and supports models in which the absorbing compounds believed to cause such atmospheric inversions are destroyed by the ultraviolet emission from the active host star (Knutson et al., 2010).

Observations with VLT-CRIRES (in 2011 June) by Rodler et al. (2012) gave  $M_{\text{p}} = 5.6 \pm 0.7 M_{\text{J}}$  and  $i = 47 \pm 6^\circ$ . This high-resolution spectroscopy provided the first 'direct' determination of the mass of a non-transiting planet.

*HD 189733*: this transiting planet was similarly observed with VLT-CRIRES at  $2.0$  and  $2.3 \mu\text{m}$  (de Kok et al., 2013). No absorption from  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ , or  $\text{CH}_4$  was detected, but a  $5\sigma$  CO absorption, at a contrast of  $4.5 \times 10^{-4}$ , revealed the planet's orbital radial velocity of  $154^{+4}_{-3} \text{ km s}^{-1}$ , yielding  $M_{\star} = 0.846 \pm 0.06 M_{\odot}$  and  $M_{\text{p}} = 1.16 \pm 0.06 M_{\text{J}}$ . Detection of Na was subsequently reported, with VLT-UVES, by Khalafinejad et al. (2017).

*51 Peg*: VLT-CRIRES observations gave  $M_{\text{p}} = 0.46 \pm 0.02 M_{\text{J}}$  and  $i = 79.6 - 82.2^\circ$  (Brogi et al., 2013).

*HD 179949*: VLT-CRIRES observations of HD 179949 b (Brogi et al., 2014) revealed CO and  $\text{H}_2\text{O}$  absorption with a combined S/N of 6.3, at a projected planet orbital velocity  $K_{\text{p}} = 142.8 \pm 3.4 \text{ km s}^{-1}$ , yielding  $M_{\text{p}} = 0.98 \pm 0.04 M_{\text{J}}$  and  $i = 67.7 \pm 4.3^\circ$ .

*$v$  And*: Keck-NIRSPEC observations detected the planet signal in  $\text{H}_2\text{O}$  for the non-transiting  $v$  And b, yielding  $M_{\text{p}} = 1.7^{+0.33}_{-0.24} M_{\text{J}}$  and  $i = 24 \pm 4^\circ$  (Piskorz et al., 2017).

For the future, simulations by de Kok et al. (2014) suggest that there are several (narrow) wavelength regions in the L-band that could yield cross-correlation signals for hot Jupiters (in  $\text{H}_2\text{O}$ ,  $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{C}_2\text{H}_2$ , and HCN) that might exceed these initial detections by a factor 2–3 for the same integration time.

Simulations for the IGRINS near-infrared spectrograph at McDonald Observatory's 2.7-m telescope (Park et al., 2014), employing similar multiple-line cross-

Table 2.3: Planetary masses based on direct planetary radial velocity determinations at high spectral resolution in the near infrared. All are based on CO absorption at around  $2\mu\text{m}$  with VLT-CRIRES. For the only transiting planet, HD 189733 b, the analysis assumes  $i = 85.5 \pm 0.1^\circ$ , as determined from transit and radial velocity measurements (Triaud et al., 2009).

Planet	$M_p (M_J)$	$i (^\circ)$	Reference
$\tau$ Boo b	$5.95 \pm 0.28$	$44.5 \pm 1.5$	Brogi et al. (2012b)
"	$5.6 \pm 0.7$	$47 \pm 6$	Rodler et al. (2012)
HD 189733 b	$1.16 \pm 0.06$	$85.5 \pm 0.1$	de Kok et al. (2013)
51 Peg b	$0.46 \pm 0.02$	$80.9 \pm 1.3$	Brogi et al. (2013)
HD 179949 b	$0.98 \pm 0.04$	$67.7 \pm 4.3$	Brogi et al. (2014)

correlation techniques, suggest that comparable measurements might be possible with IGRINS in some dozen cases (Gullikson & Endl, 2013, Table 3), with single epoch observation times between 1–100 min.

**Observational results: optical** Similar techniques have been developed in an attempt to detect *reflected* light following similar principles (Martins et al., 2013). Evidence for such a spectroscopic detection of reflected light from 51 Peg b, with HARPS, was reported by Martins et al. (2015). A wider treatment of reflected light, and phase curves, is given in Section 6.15.1.

**Coronagraphy** Riaud & Schneider (2007) proposed extracting the planet’s radial velocity signal from the residual stellar flux halo remaining in coronagraphic adaptive optics imaging in combination with the planned extremely large telescopes. The radial velocity signal is estimated to be detectable within the residual contrast ratio of  $10^3 - 10^4$ , compared to the contrast ratio of  $10^{10}$  in the absence of a coronagraph.

Kawahara et al. (2014) considered the application of coronagraphy to the direct measurement of planetary molecular lines. Even for an unresolved close-in system, the combination of a visible nuller and extreme adaptive optics could reduce the stellar photon noise, and increase the S/N of the planetary signal. For a 30-m telescope observing 55 Cnc b (at an angular separation of  $0.6\lambda/D$  in the K band) such *spectroscopic coronagraphy* could increase contrast by a factor 50–130, resulting in a S/N enhanced by a factor 3–6 for warm Jupiters and Neptunes at 10 pc. Tip-tilt error is the most crucial factor, with low-order speckles also contributing. If tip-tilt errors can be reduced to  $\leq 0.3$  mas, the S/N gain reaches 10–30, allowing the detection of warm super-Earths.

**Planet rotation** The effect of planet rotation (or spin) on the planetary radial velocity in the day-side spectra of exoplanets was considered by Kawahara (2012), who provides an analytic formula for the intensity-weighted radial velocity from the planet surface, showing that the planet radial velocity signal is distorted by its spin, and that this anomaly can be characterised by the spin radial velocity at the equator combined with a projected

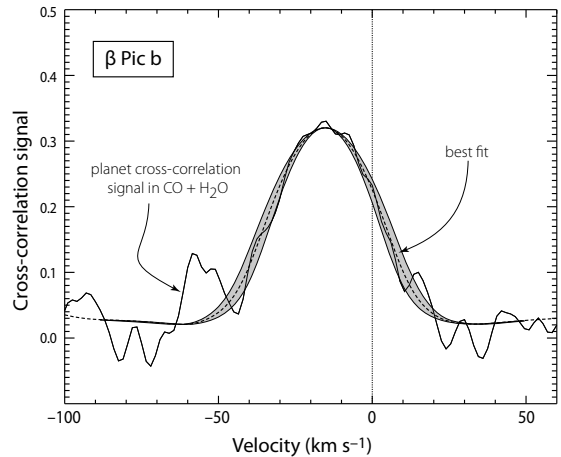


Figure 2.19: Spin of  $\beta$  Pic b: the solid line is the cross-correlation signal of the planet in the lines of CO + H<sub>2</sub>O. The dashed line indicates the best fit, rotationally broadened by  $25 \text{ km s}^{-1}$ . The grey area indicates the  $1\sigma$  uncertainty in the level of broadening of  $\pm 3 \text{ km s}^{-1}$ . From Snellen et al. (2014, Figure 2b), by permission from Nature/Springer/Macmillan Ltd, ©2014.

angle on a celestial plane between the spin axis and the axis of orbital motion  $\lambda_p$  (in a manner analogous to the Rossiter–McLaughlin effect).

Snellen et al. (2014) reported near-infrared spectroscopic observations, at  $R = 100000$ , of the young gas giant  $\beta$  Pic b. CO absorption in the planet’s thermal spectrum is blueshifted with respect to that from the host star by approximately  $15 \text{ km s}^{-1}$ , consistent with a circular orbit. The combined line profile exhibits rotational broadening of  $\sim 25 \text{ km s}^{-1}$  (Figure 2.19), meaning that  $\beta$  Pic b spins significantly faster than any planet in the solar system, although it is in line with the extrapolation of the (general) trend in spin velocity with planet mass in the solar system.

Similarly-derived spin measurements have been reported for GQ Lup, also with VLT-CRIRES (from both CO and H<sub>2</sub>O), giving  $v \sin i = 5.3^{+0.9}_{-1.0} \text{ km s}^{-1}$  (Schwarz et al., 2016a); and for PSO J318–22, with Gemini–N–GNIRS, of  $v \sin i = 17.5^{+2.3}_{-2.8} \text{ km s}^{-1}$  (Allers et al., 2016). PSO J318–22 is a free-floating planetary mass member of the  $\beta$  Pic moving group, with an estimated age of  $23 \pm 3$  Myr.

A further rotation rate, for 2M J1207 b, derived from rotational photometric modulation observed with HST–WFC3 (S9.6.5) was determined by Zhou et al. (2016d).

An overview of planet rotation in the solar system is given in Section 12.4.5, and these various spin/rotation rates (solar system planets, and exoplanet spins determined from radial velocity and photometric modulation measurements) are collected in Figure 12.15.

The relatively slow rotation of GQ Lup, for example, is most likely due to its young age,  $< 5$  Myr, viz. when it is still in the process of accreting material and angular momentum (Schwarz et al., 2016a).

**Doppler imaging** The technique of *Doppler imaging* produces two-dimensional maps of rotating objects using high-resolution spectroscopy, exploiting the varying Doppler shifts across a rotating object. The principles, and application to the surface structure of brown dwarfs and exoplanets, are described elsewhere (box, page 440).

**Application to hot Jupiters** Complementing thermal (infrared) measurements (§11.4.2), Doppler measurements can also place constraints on the ‘meteorology’ of hot Jupiters. Showman et al. (2013a) have shown that the atmospheric circulation, and Doppler signature, of hot Jupiters splits into two regimes. Under weak stellar insolation, day–night thermal forcing generates fast zonal jet streams from the interaction of atmospheric waves with the mean flow. Air along the terminator (as seen during transit) then flows toward Earth in some regions and away from Earth in others, leading to a Doppler signature exhibiting superposed blueshifted and redshifted components.

Under intense stellar insolation, however, the strong thermal forcing damps these planetary-scale waves, inhibiting their ability to generate jets. Strong frictional drag likewise damps these waves and inhibits jet formation. As a result, this second regime exhibits a circulation dominated by high-altitude, day-to-night airflow, leading to a predominantly blueshifted Doppler signature during transit. Their atmospheric circulation models suggest that cool planets like GJ 436 b lie in the first regime, HD 189733 b is transitional, while planets hotter than HD 209458 b lie in the second regime (Figure 2.20).

Additionally, the amplitude of the Doppler shifts constrains the strength of frictional drag in their upper atmospheres. Under relatively weak drag, the wind speeds at the terminator of their models of HD 209458 b reach  $4\text{--}6\text{ km s}^{-1}$ , depending on altitude and forcing conditions. Under strong drag, the wind speeds are slower.

For HD 209458 b, Snellen et al. (2010a) tentatively inferred wind speeds toward Earth of  $2 \pm 1\text{ km s}^{-1}$ , consistent with models including atmospheric drag through interaction with a planet magnetic field (Miller-Ricci Kempton & Rauscher, 2012).

### 2.5.5 Determination of inclination

The unknown inclination of most radial velocity detected systems results in the well-known  $\sin i$  dependent uncertainty on  $M_p$ . Although most of these topics are covered elsewhere, this section summarises conditions favourable for the determination of orbit inclinations.

**Astrometric constraints** Constraints are currently provided in a very few cases by high-accuracy astrometry, notably from HST (§3.7). More can be expected from Gaia (§3.9). Prospects from WFIRST and EXO are considered by Brown (2015b).

**Transit constraints** Direct inclination constraints are available for the dozen planets discovered from radial velocity observations but subsequently found to transit (see Appendix D).

**Dynamical constraints** For some multi-planet systems, mutual inclinations can be constrained by considerations of long-term dynamical stability (§2.12).

**Circumbinary systems** For planets orbiting binary stars, the stellar binary orbit may be more easily determined by astrometry, such that dynamical constraints on the inclination of the planetary orbit with respect to the plane of the sky and the

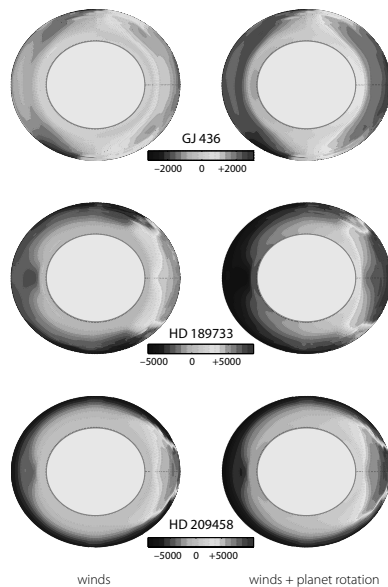


Figure 2.20: Line of sight wind velocities ( $\text{m s}^{-1}$ ) along the terminator at mid-transit, for three hot Jupiters. The radial coordinate is  $\log$  pressure, from  $2 \times 10^7\text{ Pa}$  (inside) to  $0.2\text{ Pa}$  (outside). Left: winds alone; right: wind plus planet rotation. Top to bottom: models transition from high-altitude velocities with both blue and redshifted components, to velocities that are entirely blueshifted. From Showman et al. (2013a, Figure 8), by permission of IOP Publishing/AAS.

orbit’s ascending node may also be possible. For the circumbinary HD 196885 b, the most likely configurations for the planet are either nearly co-planar (prograde or retrograde), or highly inclined orbits near the Lidov–Kozai equilibrium points at  $i = 44^\circ$  or  $i = 137^\circ$  (Giuppone et al., 2012b).

**Resonant systems** In well-observable resonant systems, monitoring of the resonant argument and the precession rates may lead to determination of the true masses. For GJ 876, for example, Rivera et al. (2005) used a 3-planet Newtonian fit to derive a minimum mass for planet d of  $M_p \sin i = 5.89 \pm 0.54 M_\oplus$  and, assuming co-planar orbits, an inclination of the GJ 876 planetary system to the plane of the sky of  $\sim 50^\circ$ .

**Tidal fixed points** Long-term orbital evolution of multi-planet systems under tidal dissipation may converge to a stationary state, the *tidal fixed point*. This is characterised by a lack of oscillations in the eccentricities and apsidal alignment among the orbits, with its precise nature dictated by mutual interactions among the planets as well as non-Keplerian effects. Under these circumstances, the  $\sin i$  degeneracy can be resolved, and true masses obtained. Details, and applicability to 61 Vir, are described by Batygin & Laughlin (2011).

**Statistical and Bayesian constraints** Statistical decoupling of the effects of unknown inclination angle on the derived mass distribution can be made if the true underlying mass distribution is known or assumed, e.g. if the true mass function is described by a power law (Brown, 2011; Lopez & Jenkins, 2012). Ho & Turner (2011) argued that the value of  $\sin i$  for a system with any particular observed value of  $M_p \sin i$  cannot be assumed to be drawn randomly from an isotropic distribution,



but rather the posterior distribution from which it is drawn depends on the intrinsic distribution of  $M_p$  for the exoplanet population being studied. They applied a Bayesian derivation to several ‘toy models’ for the intrinsic distribution of  $M_p$ .

**Effect on phase curves** Constraints on  $i$  may in principle be available as potentially detectable phase variations along the orbit (§6.15.3), which are dependent on the companion mass (Kane & Gelino, 2012a). Effects to be considered include the reflected light from the companion, which depends on its radius (itself somewhat dependent on mass), semi-major axis, eccentricity, orbital inclination and geometric albedo (determined by its atmospheric properties). As the companion mass increases, ellipsoidal variations may contribute (§6.15.3). Self-luminosity may contribute for massive planets and brown dwarfs of young age,  $\leq 1$  Gyr. Kane & Gelino (2012a) give predicted examples for the high-mass companions to HD 114762 and HD 162020.

**Radial velocity tidal signatures** Measurement of both orbital and tidal velocities for non-transiting planets may allow planet mass and inclination to be separately determined solely from radial velocity data (§2.5.3).

**Radial velocities of planets** Direct measurement of the radial velocity of a *planet*, in addition to that of the barycentric motion of the host star, eliminates the  $\sin i$  uncertainty in the orbital orientation, and provides  $M_p$  and  $i$  directly, even for non-transiting systems (§2.5.4).

## 2.6 Radial velocity instruments

### 2.6.1 Overview

A list of radial velocity instruments applied to exoplanet detection and characterisation is given in Table 2.4. It includes both large successful survey instruments, which now typically make use of many tens of nights on each of many telescopes throughout the world, as well as an incomplete list of more modest and less certain plans; it is intended to give a flavour of the activity in this field.

Most instruments are échelle spectrographs; specific ‘names’ are given when commonly used. The division between ‘early’ and ‘ongoing’ is a little arbitrary, but intended to recognise the radial velocity surveys that were being undertaken in advance of the first more secure exoplanet detection announced in 1995.

For some of the dedicated spectrographs installed on (or planned for) the largest telescopes, Figure 2.21 shows the collecting area versus spectral resolution, for both optical and near-infrared instruments.

From an optical design perspective, most modern high-resolution échelle spectrometers belong broadly to one of two families (Malacara & Thompson, 2004, Section 9.11): the double-pass Littrow design as used in SOPHIE (Perruchot et al., 2008), MIKE (Bernstein et al., 2003), PFS (Crane et al., 2010) and others; and the white-pupil design pioneered by ELODIE (Baranne et al., 1996) and used by FEROS (Stahl et al., 1999), UVES (Dekker et al., 2000), HARPS (Pepe et al., 2000), HERMES (Raskin et al., 2011) and others.

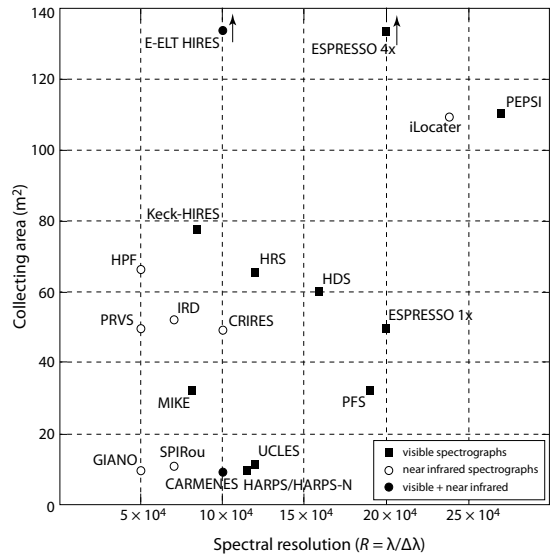


Figure 2.21: Collecting area versus resolution for existing and planned visible and near-infrared radial velocity spectrographs on large telescopes. From Crepp et al. (2016, Figure 1), with permission ©SPIE.

### 2.6.2 State-of-the-art in échelle spectroscopy

Of the numerous high-performance radial velocity instruments now operational, this section gives a short description of just two established exemplars: HARPS at the ESO 3.6-m telescope at La Silla, and HIRES at the Keck I 10-m telescope in Hawaii.

**HARPS** HARPS (High Accuracy Radial Velocity Planet Searcher) built on experience gained with ELODIE and CORALIE, and was designed to reach accuracies of around  $1 \text{ m s}^{-1}$  (Mayor et al., 2003). It has been operating at the ESO 3.6-m telescope, La Silla, since 2003 (Rupprecht et al., 2004). It is an échelle spectrograph with  $R = 115\,000$ , and operates over a spectral range 378–691 nm distributed over échelle orders  $N = 89 - 161$ . The detector consists of two CCDs (totaling  $4\text{k} \times 4\text{k}$ ,  $15 \mu\text{m}$  pixels), with one spectral order ( $N = 115$ , 530–533 nm) lost in the gap between the two.

The spectrograph is housed in a vacuum vessel, thermally controlled to a few mK to minimise spectral drifts due to temperature and air pressure variations. It is fed by two fibers, one collecting the stellar light, the other simultaneously recording either a Th–Ar reference spectrum, or the background sky. The fibers have an aperture on the sky of 1 arcsec, with image scrambling providing a uniform spectrograph pupil illumination independent of decentering.

In 60 s integration it produces a signal-to-noise ratio of 110 per pixel at 550 nm for a  $V = 6$  mag G2V star, and a photon noise error of about  $0.9 \text{ m s}^{-1}$ . Errors introduced by guiding, focus, and instrumental uncertainties lead to typical long-term radial velocity accuracies of about  $1 \text{ m s}^{-1}$  rms for spectral types later than G, and for non-rotating stars with  $v \sin i < 2 \text{ km s}^{-1}$ . Short-term precision of  $0.2 \text{ m s}^{-1}$  and long-term precision of  $0.3\text{--}0.6 \text{ m s}^{-1}$  have been achieved (Pepe & Lovis, 2008).

Table 2.4: Overview of spectroscopic instruments applied to radial velocity exoplanet searches. Resolving power,  $R = \lambda/\Delta\lambda$ , and accuracy  $\sigma$  (in  $m s^{-1}$ ), are indicative, the former tabulating the maximum value claimed, and the latter particularly dependent on magnitude (...  $\rightarrow$  ... indicates that accuracies have improved accordingly over the project's development life). References cover a mix of early and more recent reports, and instrumental descriptions, intended to provide an entry to the more detailed literature.

Telescope-instrument		Lead institute(s)	$R$ (max)	$\sigma$	Start	Reference
Early:						
CFHT 3.6-m		échelle DAO/UBC	100 000	15	1980	Campbell et al. (1988), Walker et al. (1995)
KPNO 0.9-m		échelle Kitt Peak	74 000	4	1987	McMillan et al. (1990), McMillan et al. (1994)
HJS 2.7-m		échelle U. Texas/McDonald	60 000	4–7	1988	Cochran & Hatzes (1994), Endl et al. (2008a)
Lick/Shane 3-m	HAMILTON	Lick Observatory	60 000	10–3	1986	Vogt (1987), Cumming et al. (1999)
ESO CAT 1.4-m		CES ESO planet search	100 000	20	1992	Hatzes et al. (1996), Kürster et al. (1999)
OHP 1.9-m	ELODIE	France–Switzerland	42 000	15	1993	Mayor & Queloz (1995), Baranne et al. (1996)
Whipple 1.5-m	AFOE	SAO–HAO	70 000	5	1994	Brown et al. (1994), Noyes et al. (1997a)
Ongoing:						
Keck-I 10-m		HIRES Keck	85 000	3–1	1993	Vogt et al. (1994), Vogt et al. (2000)
AAT 3.9-m	UCLES (CYCLOPS2)	Anglo–Australian	100 000	3	1998	Tinney et al. (2001), Horton et al. (2012)
ESO Euler 1.2-m	CORALIE	Geneva	50 000	7–3	1998	Queloz et al. (2000b), Tamuz et al. (2008)
McDonald HET 9.2-m		HRS U. Texas/McDonald	120 000	3	1998	Tull (1998), Cochran et al. (2007)
ESO Paranal VLT 8-m		UVES ESO	110 000	30–2	1999	Dekker et al. (2000), Joergens (2008)
TNG 3.6-m		SARG Italy/INAF	46 000	3	2001	Gratton et al. (2004)
Tautenburg 2-m		échelle Thüringer LS	67 000	3–10	2001	Hatzes et al. (2003b)
OA0 1.9-m		HIDES Japan	70 000	6	2001	Sato et al. (2005b), Sato et al. (2008a)
ESO La Silla 3.6-m		HARPS Geneva	115 000	0.3–1	2003	Mayor et al. (2003), Mayor et al. (2009a)
MPG 2.2-m	FEROS/FEROS-II	Max Planck–ESO	48 000	10	2003	Kaufer et al. (1999), Setiawan et al. (2008b)
Magellan II 6.5-m		MIKE Magellan	83 000	5	2004	López-Morales et al. (2008), Minniti et al. (2009)
Mauna Kea/Subaru 8.2-m		HDS NAOJ	160 000	4–5	2001	Noguchi et al. (2002), Aoki (2014)
BOAO 1.8-m		BOES Korea	44 000	6	2004	Izumiura (2005)
Xinglong 2.2-m		CES China	44 000	30	2005	Izumiura (2005)
Sloan 2.5-m		interferometry Exoplanet tracker	6 700	20	2006	Ge (2002), van Eyken et al. (2007)
OHP 1.9-m	SOPHIE/SOPHIE+	OHP, replaces ELODIE	75 000	6–3	2006	Perruchot et al. (2008), Bouchy et al. (2013)
Sloan 2.5-m	MARVELS*	SDSS	11 000	3–20	2008	Ge et al. (2008), Ge & Eisenstein (2009)
Magellan II 6.5-m		PFS Carnegie	190 000	1	2009	Crane et al. (2008), Crane et al. (2010)
Mercator 1.2-m	HERMES	Belgium	85 000	2.5	2009	Raskin et al. (2011)
Mt Abu 1.2-m	PARAS	India	70 000	3–5	2010	Chakraborty (2008), Chakraborty et al. (2010)
Calar Alto 2.2-m	CAFE	CAHA (Germany/Spain)	67 000	20	2011	Acetuno et al. (2013)
CTIO 1.5-m	CHIRON	Heidelberg/Yale	80 000	<1	2011	Schwab et al. (2010)
TNG 3.6-m	HARPS-N	SAO–Geneva	115 000	0.3–1	2012	Latham (2008b), Cosentino et al. (2012)
Lick/Levy 2.4-m		APF Lick Observatory	150 000	<1	2013	Vogt et al. (2014b)
Fairborn 2-m AST TOU (EXPERT-III)		Florida	110 000	–	2013	Ge et al. (2012), Ge et al. (2014)
Tubitak Turkey 1.5-m		RTT150 Ankara	55 000	10	2013	Yilmaz et al. (2013), Yilmaz et al. (2017)
SAAO–SALT 10-m	SALT-HRS	SAAO	67 000	3–4	2014	Bramall et al. (2012)
LCOGT 6 × 1-m	NRES	LCOGT (Las Cumbres)	53 000	3	2015	Eastman et al. (2014)
Mt. Hopkins/4 × 1-m	MINERVA	US (Harvard, etc)	80 000	1	2015	Swift et al. (2015a)
Mt. Graham LBT 2 × 8.4-m	PEPSI	AIP Potsdam	270 000	1	2017	Strassmeier et al. (2015)
Near infrared:						
ESO Paranal VLT 8-m		CRIRES ESO (1–5 $\mu\text{m}$ )	100 000	10–5	2007	Käufl et al. (2004), Bean et al. (2010b)
Palomar 5-m		TEDI* Berkely (0.9–2.4 $\mu\text{m}$ )	20 000	5	2007	Edelstein et al. (2007)
IRTF 3-m	CSHELL	Lowell (1.1–5.5 $\mu\text{m}$ )	46 000	15–50	2011	Crockett et al. (2011), Gagné et al. (2016)
Mauna Kea/Subaru 8.2-m		IRD NAOJ (0.97–1.75 $\mu\text{m}$ )	70 000	1	2014	Tamura et al. (2012), Kotani et al. (2014)
TNG 3.6-m		GIANO Italy/INAF (1–2.5 $\mu\text{m}$ )	50 000	7	2014	Oliva et al. (2012c)
Fairborn 2-m AST		FIRST Florida (0.8–1.8 $\mu\text{m}$ )	72 000	–	2014	Ge et al. (2007)
McDonald 2.7-m		IGRINS Texas/Korea (1.5–2.5 $\mu\text{m}$ )	40 000	–	2014	Gullikson & Endl (2013), Park et al. (2014)
McDonald HET 9.2-m		HPF Penn State (0.9–1.7 $\mu\text{m}$ )	50 000	1–3	2017	Mahadevan et al. (2014b)
Mauna Kea CFHT 3.6m		SPIRou FRA/CAN (0.9–2.4 $\mu\text{m}$ )	70 000	1	2017	Delfosse et al. (2013b)
IRTF 3-m		iSHELL Lowell (1.1–5.2 $\mu\text{m}$ )	80 000	<3	2017	Rayner et al. (2016)
Mt. Graham LBT 2 × 8.4-m		iLocater USA/ITA/DEU (0.9–1.3 $\mu\text{m}$ )	240 000	0.1	2018	Crepp et al. (2016)
Magellan 6.5-m	Maroon-X	Chicago (0.7–0.9 $\mu\text{m}$ )	80 000	0.7	2018	Seifahrt et al. (2016)
Gemini 8.1-m	PRVS	Gemini (0.9–1.7 $\mu\text{m}$ )	50 000	7–10	study	Ramsey et al. (2008), Jones et al. (2008c)
Near infrared+optical:						
Calar Alto/CAHA 3.5-m	CARMENES	DEU/ESP (0.55–1.7 $\mu\text{m}$ )	82 000	1	2016	Quirrenbach et al. (2012), Reiners et al. (2018)
TNG 3.6-m	GIARPS	GIANO+HARPS (0.38–2.45 $\mu\text{m}$ )	–	–	2018	Claudi et al. (2016)
Future (optical and/or infrared):						
LAMOST		EDI China	10 000	1	study	Zhang (2011)
Small telescopes		RHEA Macquarie, Australia	75 000	–	2017	Feger et al. (2014), Feger et al. (2016)
ESO VLT 4 × 8-m		ESPRESSO ESO (Geneva, Bern)	200 000	0.1	2017	Liske et al. (2009), Pepe et al. (2014b)
Lowell DCT 4.3-m		EXPRES Yale (0.7–0.9 $\mu\text{m}$ )	150 000	<0.3	2017	Jurgenson et al. (2016)
ESO Paranal VLT 8-m		CRIRES+ ESO	100 000	<5	2018	Oliva et al. (2012b)
ESO La Silla 3.6-m		NIRPS Montreal/Geneva (1–1.8 $\mu\text{m}$ )	100 000	–	2019	Conod et al. (2016)
LCO GMT 24.5-m		G–CLEF Magellan	120 000	0.1	2022	Ben-Ami et al. (2016)
E–ELT 42-m		HIRES ESO/INAF (0.37–2.5 $\mu\text{m}$ )	100 000	0.01	2024	Oliva et al. (2015a), Marconi et al. (2016)

Lovis et al. (2008) summarised results from the first three years, and detail the global error budget taking account guiding accuracy and photon noise. The HARPS guaranteed time high-precision sample is presented in Sousa et al. (2008).

A polarimetric unit, HARPSpol (Piskunov et al., 2011), allows a full polarisation spectral analysis. This has been applied to the discovery of various massive magnetic stars (Alecian et al., 2011, 2014), observations of the planet-host  $\tau$  Boo (Borsa et al., 2015; Mengel et al., 2016), and others.

**Keck–HIRES** A second example of high-accuracy radial velocity instrumentation is the Keck I 10-m telescope on Mauna Kea, Hawaii, equipped with the HIRES échelle spectrometer. HIRES was one of the five first-light instruments for the Keck I telescope, designed and built at UCO/Lick Observatory (Vogt et al., 1994). The project started in 1988, and achieved first light in 1993. While described as a conventional échelle spectrometer, it was designed to have a relatively large order separation, at the expense of overall wavelength coverage, to allow both for accurate sky subtraction (for faint objects), and for image slicing (for bright objects).<sup>9</sup>

In the configuration described by Vogt et al. (2000), the resolving power is  $R = 80\,000$ , and the spectra span a wavelength range from 390–620 nm. Wavelength calibration uses an iodine absorption cell.

### 2.6.3 Other optical spectrographs

This section gives a summary of some of the more ambitious or pioneering instruments recently undertaken, ordered alphabetically by instrument name. Others are listed in Table 2.4.

**APF (Lick)** The Lick Observatory Automated Planet Finder (APF) uses the Levy spectrometer at the Mt Hamilton 2.4-m telescope (Vogt et al., 2014b). Wavelength calibration is provided by an iodine cell. First light was in June 2013, with robotic operation since January 2014. First discoveries, based on Keck–HIRES candidates, were GJ 687 (Burt et al., 2014) and the 4-planet system HD 141399 (Vogt et al., 2014a).

**CHIRON (CTIO)** CHIRON is a high-resolution échelle spectrograph at the 1.5-m CTIO telescope since 2011, covering 415–880 nm, and yielding  $R = 79\,000 - 136\,000$  (Tokovinin et al., 2013). The échelle grating is housed in a vacuum enclosure, with temperature held to  $\pm 0.2^\circ\text{C}$ . Stable illumination is provided by light-scrambling octagonal multimode fibers, with an iodine cell for wavelength calibration.

**EPDS (WIYN)** The NASA-funded Extreme Precision Doppler Spectrometer (EPDS) is will be operational on the 3.5-m WIYN telescope in 2018, timed with the data flow from the Transiting Exoplanet Survey Satellite (TESS) mission. It is a  $R > 70\,000$  fiber-fed system targeting an accuracy of  $0.1\text{--}0.2\text{ m s}^{-1}$ , led by Pennsylvania State University.

<sup>9</sup>Given the impact of discoveries by Keck–HIRES (Table 2.5), it is noteworthy that amongst the first-light science originally foreseen (including quasar absorption lines, Be in the early Universe, Li abundances, and asteroseismology), exoplanet detection and characterisation did not figure (Vogt et al., 1994).

**HARPS–N (TNG)** The visible spectrograph HARPS–North has been deployed at the Telescopio Nazionale Galileo (TNG, La Palma) since 2012. Based on HARPS, it exploits an ultra-stable environment, includes better scrambling using octagonal fibers and a tip-tilt system to increase image sharpness, and targets measurements under  $1\text{ m s}^{-1}$  (Cosentino et al., 2012). Goals include Kepler field observations, with significant TNG time devoted to it (Hébrard et al., 2013a; Berdiñas et al., 2016).

**HDS (Subaru)** The High Dispersion Spectrograph (HDS) is the échelle spectrograph for the Subaru Telescope (Noguchi et al., 2002). It provides  $R = 90\,000 - 160\,000$ , sensitivity from 300 nm to  $1\ \mu\text{m}$ , and single exposures covering a range of 150–250 nm. New image slicers that improve the efficiency at very high resolution were installed in 2011 (Aoki, 2014).

**PFS (Magellan)** The Carnegie Planet Finder Spectrograph (PFS) operates at the Magellan Clay 6.5-m telescope at Las Campanas Observatory, Chile (Crane et al., 2010). It is optimised for high precision and high stability, covers 388–668 nm across 64 orders, provides  $R = 38\,000$ , and uses an iodine cell as wavelength reference, achieving accuracies  $\sim 1\text{ m s}^{-1}$ .

**Meter-class telescopes** Instrument advances (e.g. fiber feeds) have enabled lower-cost instruments on meter-class telescopes. These include: in India, the Mt Abu 1.2-m (Chakraborty et al., 2008); in Hungary, the Piszkestető 1.0-m and Szombathely 0.5-m (Csák et al., 2014); in Germany, the Großschwabhausen 0.9-m (Mugrauer et al., 2014a); and in Slovakia, the Stará Lesná 0.6-m (Pribulla et al., 2015; Garai et al., 2017).

### 2.6.4 Infrared spectrographs

**Rationale** As radial velocity work in the optical has advanced over the past two decades, interest in high-resolution spectroscopy in the near infrared has intensified, confronting a new range of technical challenges posed by the detectors, cryogenic operation, atmospheric transmission, and wavelength calibration.

To a large extent this interest has been motivated by the search for planets around late M dwarfs. These are brighter in the infrared, less massive (accentuating the radial velocity effect for a given planet mass) and, being cooler, their habitable zones lie closer to the host star. Habitable-zone planets are therefore more easily detectable, and over shorter time spans (Reiners et al., 2010; Rodler et al., 2011).

Simulations based on stellar atmospheric models suggest that the highest precision is achieved around  $1\ \mu\text{m}$  for cool M dwarfs and around  $1.25\ \mu\text{m}$  for L dwarfs (Rodler et al., 2011). Line intensity and continuum air-glow emission in the H-band, important for instrument design, is described by Oliva et al. (2013, 2015b). They identified some 1500 emission lines over the range  $0.97\text{--}2.4\ \mu\text{m}$ , of which some 80% are OH transitions.

The influence of star spots is also reduced in the near-infrared compared with the visible (Desort et al., 2007; Barnes et al., 2011a), such that a comparison at optical and infrared wavelengths can help to discriminate planet-induced velocity changes from stellar jitter.

For these reasons, various new instruments are becoming operational in the infrared. This following summarises a few representative instruments, ordered alphabetically, with a more complete listing in Table 2.4.

**CRIRES+ (VLT)** Upgrade of VLT-CRILES (Figueira et al., 2010c) to the cross-dispersed CRIRES+ aims for a significant improvement in sensitivity and wavelength coverage (0.9–5.4  $\mu\text{m}$ ) as a result of its improved detectors (Oliva et al., 2012b). First light is due in 2018 Q2.

**GIANO (TNG)** GIANO is a high-resolution ( $R = 50000$ ) infrared spectrograph at the 3.6-m Telescopio Nazionale Galileo, La Palma, covering 0.95–2.5  $\mu\text{m}$  in a single exposure (Oliva et al., 2012a,c). It has been operational since 2014. The accuracy is some 7  $\text{m s}^{-1}$  with respect to telluric lines, with an rms calibration accuracy of 300  $\text{m s}^{-1}$  as determined from U–Ne lamps.

**HPF (HET)** The Habitable zone Planet Finder (HPF) is a stabilised fiber-fed near-infrared spectrograph for the Hobby–Eberly 10-m telescope (Mahadevan et al., 2012; Stefansson et al., 2016). It covers the Y and J bands (0.9–1.7  $\mu\text{m}$ ) to provide precise radial velocities optimised for mid-M dwarfs. It includes a cryostat cooled to 200 K, dual fiber-feed, a gold-coated échelle grating, and a Hawaii–2RG (H2RG) detector. Wavelength calibration uses a U–Ne lamp, with tests of laser frequency combs ongoing. First light, on GJ 3470, was reported in 2017 November.

**IGRINS (McDonald)** The Immersion Grating Infrared Spectrometer (IGRINS) is a compact high-resolution near-infrared échelle spectrograph for the 2.7-m Harlan J. Smith telescope at the McDonald Observatory, covering 1.45–2.45  $\mu\text{m}$  in a single exposure with  $R = 40000$  (Gullikson & Endl, 2013; Park et al., 2014). The primary disperser is a silicon immersion grating. Individual volume phase holographic gratings serve as cross-dispersers for separate spectrographs covering the H and K bands, with two 2048  $\times$  2048 Teledyne HAWAII–2RG detectors.

**IRD (Subaru)** The Infrared Doppler Instrument (IRD) at the Subaru 8.2-m also aims at detecting Earth-like planets around nearby M dwarfs (Tamura et al., 2012; Kotani et al., 2014). It is a fiber-fed, near-infrared spectrometer operating over 0.97–1.75  $\mu\text{m}$  at  $R = 70000$ . New technologies to achieve 1  $\text{m s}^{-1}$  include very low thermal expansion ceramic for most of the optical components including the optical bench, and use of a laser frequency comb for wavelength calibration.

**SPIRou (CFHT)** SPIRou (SpectroPolarimètre Infra-Rouge) at the CFHT 3.6-m is a near-infrared spectropolarimeter covering the range 0.9–2.4  $\mu\text{m}$ , providing unpolarised and polarised spectra at  $R = 73500$ , with accuracies of 1  $\text{m s}^{-1}$  (Delfosse et al., 2013b; Moutou et al., 2015a). First light is due in early 2018.

### 2.6.5 Optical–infrared spectrographs

**Rationale** Simultaneous observations in the optical and near infrared (Table 2.4, see also Figure 2.15), are likely to be particularly important in extending the M dwarf exoplanet surveys, while at the same time providing strong constraints on wavelength-dependent noise sources such as star spots (e.g. Reiners et al., 2010; Ma & Ge, 2012; Anglada-Escudé et al., 2013a).

This approach has been demonstrated, for example, with two of the stable M dwarfs observed with HARPS,

Barnard’s star (GJ 699) and GJ 588. Anglada-Escudé et al. (2013a) showed that Barnard’s star is stable to 0.009  $\text{m s}^{-1}$  over 4 yr, and that the radial velocity signals correlated with activity disappear when using the reddest part of the HARPS wavelength range. Similar effects are seen in the observations of T Tauri stars at 670 nm and 2.3  $\mu\text{m}$  (Crockett et al., 2012).

CARMENES, with its dual optical–infrared spectrograph arms, has been operational since the start of 2016. E–ELT–HIRES is adopting a similar approach. GIARPS is an ongoing project to operate the HARPS–N (optical) and GIANO (near infrared) instruments simultaneously at the TNG (Claudi et al., 2016). NIRPS is an infrared complement to the HARPS instrument at the ESO 3.6-m telescope, due for operation in 2019.

**CARMENES (CAHA)** CARMENES (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Echelle Spectrographs) is a German–Spanish project, operational at the CAHA 3.5-m telescope in southern Spain since the start of 2016 (Quirrenbach et al., 2011a, 2012, 2014).

It consists of two temperature-stabilised échelle spectrographs together covering 0.55–1.7  $\mu\text{m}$ , fed by (agitated octagonal) fibers from the Cassegrain focus, and employing simultaneous calibration with emission-line lamps (Th–Ne in the optical,  $^{235}\text{U}$ –Ne in the infrared) or with a Fabry–Pérot étalon. The visible-light arm (0.52–0.96  $\mu\text{m}$ ,  $R = 93000$ , employing a 4096  $\times$  4096 e2v CCD) is operated at 12 C, while the near-infrared arm (0.96–1.71  $\mu\text{m}$ ,  $R = 82000$ , employing two 2048  $\times$  2048 HAWAII–2RG infrared detectors) is cooled to 140 K.

Of relevance for mid- to late-M stars, the efficiency has been optimised around 1.0  $\mu\text{m}$  (Y band). A survey of 300 M dwarfs has an assignment of 600 nights between 2016–18, with ~60 observations per star. It emphasises very cool stars with spectral type M4V or later, but also includes earlier and brighter M dwarfs (Reiners et al., 2017). With a long-term radial velocity precision target of 1  $\text{m s}^{-1}$  per measurement, the goal is to detect a 2  $M_{\oplus}$  planet in the habitable zone of an M5V star, and super-Earths of  $\lesssim 5 M_{\oplus}$  across the habitable zones.

First results include follow-up observations in the visual channel of 9 known M dwarfs, with the confirmation of all except one, and the discovery of a second planet in GJ 1148 (Trifonov et al., 2018). Estimated (V-channel) formal rms uncertainties are around 1–2  $\text{m s}^{-1}$ , comparable to those for HARPS and Keck–HIRES (their figure 14). The first discovery, a planet around the 10.7 pc M dwarf GJ 617A (HD 14739), for which they estimate  $\sigma_{\text{VIS}} = 1.7 \text{ m s}^{-1}$  and  $\sigma_{\text{NIR}} = 8.6 \text{ m s}^{-1}$  also made use only of the visual channel (Reiners et al., 2018).

**NIRPS (La Silla)** NIRPS (Near Infra Red Planet Searcher) is an  $R = 100000$  infrared spectrograph to complement the HARPS instrument at the ESO 3.6-m telescope, under development by a consortium led by the University of Montreal and the Geneva Observatory. It comprises an adaptive optics and fiber feed system with a 0.4 arcsec field, employing a Shack–Hartmann wavefront sensor with 14  $\times$  14 sub-apertures, a Hawaii 4RG 4k  $\times$  4k detector, and operating between 0.98–1.8  $\mu\text{m}$  (Conod et al., 2016). Operation is scheduled for 2019 August.

**GIARPS (TNG, La Palma)** GIARPS targets the simultaneous use of the HARPS–N (optical) and GIANO–B (infrared) spectrographs to achieve high-resolution spectroscopy over 0.38–2.45  $\mu\text{m}$  in a single exposure (Claudi et al., 2016).

### 2.6.6 Future instrument plans

Future instruments aim for significant improvements in radial velocity accuracy over current levels of 0.3–0.5 m s<sup>-1</sup>, with target accuracies ~ 0.1 m s<sup>-1</sup> or better.

**ESPRESSO (VLT)** ESPRESSO (Echelle Spectrograph for Precision Super Stable Observations, Pasquini et al., 2009; Pepe et al., 2013b, 2014b) will be installed in the Combined Coudé Laboratory of the ESO–VLT, and linked to the four Unit Telescopes through optical coudé trains. It can be operated either with a single Unit Telescopes, or with up to four combined incoherently for a gain of some 1.5 mag. It targets a radial velocity precision at the 0.1 m s<sup>-1</sup> level, with a limiting magnitude 2 mag fainter than HARPS (Dumusque et al., 2011b). It will test a number of new subsystems foreseen for HIRES for E–ELT, including fiber scrambling, CCD thermal stabilisation, and the use of laser frequency combs for wavelength calibration. It saw first light in 2017 November.

**iLocater (LBT)** iLocater is a cross-dispersed échelle spectrograph covering the Y and J-bands (0.97–1.30 μm), with  $R = 150\,000 - 240\,000$ , and targeting 0.1 m s<sup>-1</sup> accuracies (Crepp et al., 2016). It aims to operate at the diffraction limit of the individual 8.4-m diameter telescopes (each using extreme adaptive optics), with the use of single mode optical fibers to eliminate modal noise (§2.3.8). Priority will be assigned to follow-up measurements for the TESS mission. In contrast with (all other) seeing-limited spectrometers, iLocater will also reduce contamination from neighbouring stars permitting Doppler studies of close-separation binaries. Operation is targeted for 2018.

**HIRES (E–ELT)** E–ELT HIRES is a merger, dating from 2012, of two previous high spectral resolution instrument concepts, CODEX (COsmic Dynamics EXperiment, an ultra-stable optical, 0.37–0.71 μm,  $R = 120\,000$  spectrograph) and SIMPLE (a near-infrared, 0.84–2.5 μm,  $R = 130\,000$  adaptive optics-assisted spectrograph; Origlia et al. 2010). A goal of CODEX was to detect the expansion of the Universe directly, by measuring the Doppler shift of high-redshift quasar Ly- $\alpha$  absorption lines as a function of time (the ‘Sandage test’). CODEX incorporated high-stability slanted volume phase holographic gratings, fiber-optic scrambling to reduce the impact of guiding errors, and wavelength calibration using laser frequency combs (Pepe & Lovis, 2008; Pasquini et al., 2008a,b; Liske et al., 2009).

HIRES is currently foreseen as a dual-channel (optical–infrared) spectrograph, providing  $R \sim 100\,000$  over 0.37–2.5 μm (Marconi et al., 2016). Exoplanet requirements foresee a radial velocity accuracy of ~ 0.1 m s<sup>-1</sup>, while the Sandage test requires a night time stability, and absolute wavelength calibration, maintained over decades, of 0.02 m s<sup>-1</sup>. The latter are considered as goals rather than design drivers. The HIRES Phase A study should be completed in March 2018. First light is tied to that of the E–ELT, currently 2024.

### 2.6.7 Externally dispersed interferometry

**Background** Various interferometric-based techniques have been applied to spectroscopy and radial velocity measurements in the past, although not for exoplanets. In *Fourier transform spectroscopy*, for example, light enters a Michelson interferometer through a beam-splitter. The resulting interference pattern, in frequency space, depends on the path delay within the

interferometer, and the recorded intensity is a measure of the light’s temporal coherence. One mirror is moved to introduce a variable path length, the temporal coherence is measured as a function of this path delay,  $I(\delta)$ , and the spectrum is recovered by Fourier transform of  $I(\delta)$ . Fourier transform spectroscopy provides for very high spectral resolution, but only for very bright sources due to the inefficient use of photons which are sampled only sequentially at each path delay setting.

Fixed delay interferometers with narrow band passes isolating a single spectral line have used this principle for solar measurements since the 1980s, reaching accuracies of around 3 m s<sup>-1</sup> (e.g. Kozhevnikov et al., 1995, and references). Other approaches have employed a more extended optical delay path range within the interferometer, without resorting to physical scanning, for example using gratings or holographic gratings (*holographic heterodyne spectroscopy*) in place of the mirrors (e.g. Connes, 1985; Frandsen et al., 1993; Douglas, 1997).

**Use of a post-disperser** The combination of a Michelson interferometer with post-disperser was suggested for spectroscopy already by Edser & Butler (1898). It entered the exoplanet literature with the work of Erskine & Ge (2000), described as a *fringing spectrometer*. Subsequent developments have been described under the epithets of a *dispersed fixed-delay interferometer*, DFDI (Wang et al., 2011, 2012a), or an *externally dispersed interferometer*, EDI (Ge, 2002; Ge et al., 2002b; Erskine, 2003; Erskine et al., 2003; van Eyken et al., 2004; Mahadevan et al., 2008b; van Eyken et al., 2010; Wan et al., 2011; Erskine et al., 2016).

A prototype instrument (‘exoplanet tracker’) was used to confirm the known exoplanet, 51 Peg b, at the KPNO 2.1-m by van Eyken et al. (2004), and as the basis of the W.M. Keck Exoplanet Tracker instrument (Mahadevan et al., 2008a,b).

The first planet discovered using this technique was HD 102195 (ET1), made at the KPNO 0.9-m, and confirmed with the KPNO 2.1-m and the HET–HRS (Ge et al., 2006), and subsequently by HARPS (Melo et al., 2007). The planet has  $P = 4.1$  d and  $M_p \sin i = 0.49 M_J$ .

**MARVELS** The concept also underlies the MARVELS survey at Apache Point Observatory (Multi-object APO Radial-Velocity Exoplanet Large-area Survey). MARVELS formed part of the six-year Sloan Digital Sky Survey SDSS III extension, operating between 2008–14. Its scientific goal was to monitor 11 000  $V = 8 - 12$  stars over 800 sq. deg. for six years. The survey targeted 90% F8 and later main sequence stars and subgiants, and 10% G and K giants with  $V = 7.6 - 12$  (van Eyken et al., 2007; Ge & Eisenstein, 2009; Ge et al., 2009). The instrument acquired radial velocities, at 3–20 m s<sup>-1</sup> depending on  $V$  magnitude, for 60 objects simultaneously in the 3° field, by lining up the distinct low-resolution spectra across the CCD (Wan et al., 2006). A trial survey of 420  $V = 8 - 12$  mag solar-type stars in 2006 was reported by Ge et al. (2007).

The survey discovered a number of low-mass (sub-)stellar companions, and a few candidate brown dwarfs, designated

MARVELS-n (Fleming et al., 2010; De Lee et al., 2013; Jiang et al., 2013b; Grieves et al., 2017). Of these, MARVELS-1 (TYC 1240-945-1) was subsequently re-classified as a face-on binary (Lee et al., 2011b; Wright et al., 2013), while a further candidate, TYC 3010-1494-1, proved to be a long-period high-eccentricity spectroscopic binary (Mack et al., 2013). A giant planet (MARVELS-7 b) and a brown dwarf candidate (MARVELS-7 c) were discovered orbiting the close binary HD 87646, representing the first close binary with more than one substellar circum-primary companion (Ma et al., 2016a).

Including 10 new MARVELS candidates in the 'brown dwarf desert' (§2.10.5), Grieves et al. (2017) derived a brown dwarf occurrence rate around solar-type stars with  $P < 300$  d of 0.56%.

**Related initiatives** An All-Sky Extrasolar Planet Survey (ASEPS), using wide-field telescopes to monitor stars to  $V = 12-13$  mag, targeted increasing the number of exoplanet detections by a factor of 10-100 (Ge, 2007; Ge et al., 2007). Observing strategies for large-scale multi-object surveys were simulated by Kane et al. (2007). A similar instrument concept has been considered for LAMOST (Zhang, 2011). A prototype at the BTA 6-m telescope is described by Panchuk et al. (2009, 2010).

Broadly similar principles are used in the *dispersed Fourier transform spectrometer* (dispersed FTS) considered by the USNO (Hajian et al., 2007). But rather than operating at a fixed delay position, the interferogram of the Fourier transform spectrometer is coarsely sampled over a wide range of delay positions, so that a complete high-resolution broad-band spectrum can be reconstructed. The addition of a post-disperser essentially creates several thousand separate narrow-band Fourier transform spectrometers operating in parallel.

**Extension to the infrared** The same technique can be used at longer wavelengths. The TEDI instrument (TripleSpec Exoplanet Discovery Instrument) extended the concept to the near infrared (0.9-2.4  $\mu\text{m}$ ) by coupling a wide-angle Michelson interferometer to the existing  $R = 3000$  TripleSpec échelle spectrometer at the Palomar 5-m telescope, whose spectral resolution alone is insufficient for exoplanet radial velocity measurement. The instrument is used in phase uniform mode, and both interferometer outputs are relayed to the spectrograph (Edelstein et al., 2007, 2008; Muirhead et al., 2011; Erskine et al., 2014).

### 2.6.8 Absolute accelerometry

A conceptually different approach to determining radial velocity *variations* is to measure accelerations.

Connes (1985, 1994) proposed a system in which the stellar light, and light from a white light source, are passed alternately through a Fabry-Pérot étalon. A feedback loop adjusts the étalon spacing to achieve coincidence. A tunable laser tracks the Fabry-Pérot spacing, and a measurable beat signal is generated from a stabilised laser. The objective is to lock onto the stellar lines, and to monitor fluctuation using terrestrial frequency standards. The radial velocity of the source can be assigned some arbitrary value at some reference time and, accounting for the (known) heliocentric correction terms, subsequent observations provide the absolute acceleration with respect to the observer.

Connes (1985) estimated that for a  $P = 10$  yr orbit, a 1 m telescope observing a 10 mag star for 10 yr and an

observing time of  $10 \times 1$  h per year, would reach an acceleration amplitude of  $2 \times 10^{-5} \text{ m s}^{-2}$ , corresponding to a radial velocity error of  $0.1 \text{ m s}^{-1}$ . A laboratory system was built and tested (Schmitt, 1997; Bouchy et al., 1999).

A more recent assessment of the merits of this approach are given by Panchuk et al. (2010).

## 2.7 Introduction to the radial velocity results

### 2.7.1 The first radial velocity exoplanets

Early radial velocity surveys (Table 2.4), on a relatively small number of stars, were primarily aimed at characterising the substellar/brown dwarf mass function by searching for binary companions of main-sequence stars with masses below  $1 M_{\odot}$  (Campbell et al., 1988; Marcy & Moore, 1989; Marcy & Benitz, 1989; McMillan et al., 1990; Duquennoy & Mayor, 1991; Tokovinin, 1992). Some were part of programmes to establish improved IAU radial velocity standards (Latham et al., 1989).

As accuracies improved towards plausible planetary signals of  $10-20 \text{ m s}^{-1}$ , existing groups intensified their efforts, and others started new programmes, leading to the monitoring of many more stars over several years.<sup>10</sup>

The first radial velocity detections were announced cautiously, and only substantively confirmed some years later. Thus Campbell et al. (1988) identified a possible  $P = 2.7$  yr,  $1.7 M_{\text{J}}$  object around  $\gamma$  Cep, parameters which were subsequently questioned (Walker et al., 1992), but which were eventually confirmed by the 1981-2002 study of Hatzes et al. (2003a). Latham et al. (1989) reported a  $P = 84$  d,  $11 M_{\text{J}}$  companion to HD 114762, which they suggested was a probable brown dwarf. These values were confirmed by Cochran et al. (1991), and further refined by Butler et al. (2006b). Hatzes & Cochran (1993) reported a possible  $P = 558$  d,  $2.9 M_{\text{J}}$  companion to the K giant HD 62509 ( $\beta$  Gem), parameters again substantially confirmed in the 25-year baseline study by Hatzes et al. (2006).

**The discovery of 51 Peg b** The discovery of a very short-period  $P = 4.2$  d ( $a = 0.05$  au)  $0.47 M_{\text{J}}$  planet surrounding the star 51 Peg, was announced by Mayor & Queloz (1995). The discovery was promptly confirmed by the Lick Observatory group, who were also quickly able to report two new planets around stars that they had been monitoring: 70 Vir (Marcy & Butler, 1996) and 47 UMa (Butler & Marcy, 1996). The compelling realisation that planetary mass objects existed around main

<sup>10</sup>Walker (2012) provides a recent perspective on the radial velocity exoplanet searches carried out in the 1970s-1980s, and states 'It is quite hard nowadays to realise the atmosphere of scepticism and indifference in the 1980s to proposed searches for extrasolar planets. Some people felt that such an undertaking was not even a legitimate part of astronomy'.

sequence stars marked the start of a substantive and world-wide acceleration in exoplanet research.

The reality of 51 Peg b was the subject of some early and intense controversy. In part this was motivated by its unexpectedly short orbital period and close proximity to the parent star (although see footnote, page 62). But an alternative explanation – that the radial velocity shifts arose from non-radial oscillations – was also put forward to explain possible distortions in the absorption line bisector. Studies that followed (Gray, 1997; Hatzes et al., 1997; Marcy et al., 1997; Gray & Hatzes, 1997; Willems et al., 1997; Brown et al., 1998a,b; Gray, 1998; Hatzes et al., 1998a,b) finally resulted in a consensus that the planet hypothesis was the most reasonable.

Recent perspectives have been given by Mayor & Queloz (2012) and Cenadelli & Bernagozzi (2015).

### 2.7.2 Example radial velocity curves

Out of nearly 700 planets now discovered from radial velocity measurements, a small selection of graphical results is shown in Figures 2.22–2.25 as examples of the variety, measurement quality, and orbit reconstruction possibilities. These figures relate to the following systems (and where all radial velocity derived mass estimates are implicitly uncertain by the factor  $\sin i$ ):

HD 4113 (G5V): Tamuz et al. (2008) used CORALIE to discover a  $1.63M_J$  planet in a highly eccentric ( $e = 0.90$ )  $a = 1.28$  au,  $P = 526$ -d orbit. The radial velocity curve shows a sharp, strongly asymmetric form arising from the eccentricity (Figure 2.22), and an underlying linear trend attributable to an outer, longer-period planet.

55 Cnc (G8V): Fischer et al. (2008) used Lick and Keck observations (1989.1–2007.4), to characterise five orbiting planets. Planets were identified by periodogram analysis of residuals to successive Keplerian fits (Figure 2.23).  $\{M_p \sin i, P\}$  ( $M_J$ , d) are  $\{0.024, 2.8\}$ ,  $\{0.83, 14.6\}$ ,  $\{0.17, 44.4\}$ ,  $\{0.15, 261\}$ ,  $\{3.9, 5400\}$ .

HD 40307 (K2.5V): Mayor et al. (2009b) used HARPS to characterise the orbits of three ‘super-Earth’ planets (Figure 2.24; the total radial velocity semi-amplitude of the combined three-planet signal is only  $\sim 6 - 7 \text{ m s}^{-1}$ ).  $\{M_p \sin i, P\}$  ( $M_\oplus$ , d) are  $\{4.2, 4.3\}$ ,  $\{6.8, 9.6\}$ ,  $\{9.2, 20.5\}$ .

61 Vir (G5V): Vogt et al. (2010b) used 4.6 years of Keck-HIRES and AAT data to characterise this ‘super-Earth and two Neptune’ planetary system (Figure 2.25). The planets are all in low-eccentricity orbits; their  $\{M_p \sin i, P\}$  ( $M_\oplus$ , d) are  $\{5.1, 4.2\}$ ,  $\{18.2, 38\}$ ,  $\{24.0, 124\}$ .

### 2.7.3 Present radial velocity census

Apart from the extreme planetary system around the pulsar PSR B1257+12, and until the first transiting planet discovered by photometry in 2003 (OGLE-TR-56; Konacki et al., 2003a), almost the first hundred planets around normal main-sequence stars were discovered

Table 2.5: Number of planets discovered by the 20 most prolific radial velocity instruments, based on the NASA Exoplanet Archive compilation as of the end of 2017. This listed 662 planets discovered by radial velocity measurements. A planet discovered by observations with  $N$  instruments, is counted for  $1/N$  discoveries by each. A total of 17 radial velocity discoveries are accounted for by other observatories/instruments.

Observatory/instrument	Number
Keck-HIRES	162
ESO-HARPS	154
Euler-CORALIE	51
AAT-UCLES	40
Lick-Hamilton	32
HET-HRS	28
OHP-SOPHIE	27
Okayama-HIDES	26
TNG-HARPS-N	23
OHP-ELODIE	18
Bohunsan-BOES	15
Magellan-MIKE	13
Subaru-HDS	10
ESO-FEROS	10
Tautenburg	8
APF-Levy	8
McDonald-HJS	6
ESO-CHIRON	5
Whipple-TRES	5
Magellan-PFS	4

using radial velocity techniques. The number of radial velocity discoveries continues to rise, as enlarged surveys, higher measurement accuracies, and longer temporal baselines take effect (Table 2.5).

As of 2010 November 1 (the first edition of this handbook), there were 494 known exoplanets, of which 461 in 390 systems (45 multiple) had measured radial velocity orbits, and 358 had been discovered by radial velocity measurements.

As of the end of 2017 there were 3572 planets (some 2500 from Kepler/K2) of which 662 planets, including 102 multiple systems, had been discovered by radial velocity measurements. A concise bibliography of the radial velocity planets is given in Appendix C.

Figure 2.26 shows the planets discovered from radial velocity measurements by year, as a function both of  $M_p$  (ordinate) and semi-major axis  $a$  (circle size). The decreasing lower mass bound with time reflects the improving instrumental accuracy leading to smaller detectable values of  $K$ . For a given planet mass,  $K \propto P^{-1/3}$  (Equation 2.27), which explains their preferentially smaller  $a$ .

Figure 2.27 illustrates the region probed by the radial velocity discoveries, compared with transit and astrometric detections at current and projected accuracies.

Figure 2.28 shows the number of exoplanets discovered to date by radial velocity monitoring as a function of spectral type.

As discoveries proceed, more significant statistical

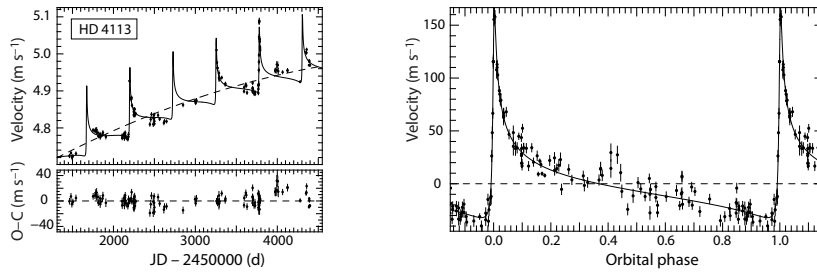


Figure 2.22: Left: radial velocity measurements for HD 4113, observed with CORALIE, with the best-fit Keplerian solution including a linear drift (residuals below). Right: the same measurements folded at  $P = 526.58$  d, yielding  $K = 97.7$   $\text{m s}^{-1}$ ,  $a = 1.28$  au,  $e = 0.90$ , and  $M_p \sin i = 1.63 M_J$ . The planet–star separation varies between 0.12–2.4 au. The long-term drift, and its curvature, may imply a brown dwarf companion at 8–20 au, with  $P \sim 20 - 90$  yr. From Tamuz et al. (2008, Figure 1), reproduced with permission © ESO.

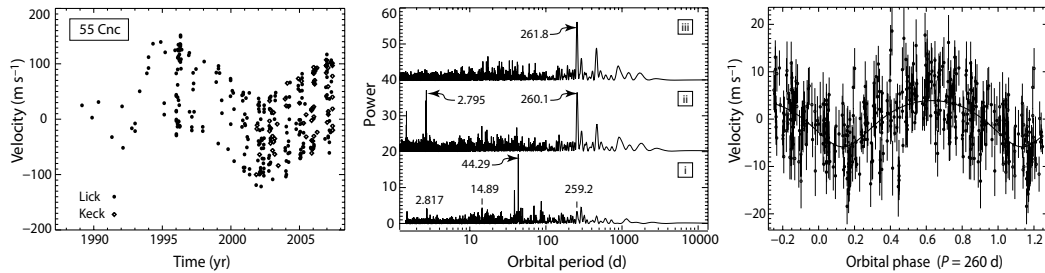


Figure 2.23: The five-planet system 55 Cnc. Left: velocities from Lick/Keck (1989.1–2007.4). Middle: periodograms of residuals to successive Keplerian models: (i) with respect to the 2-planet (14.65 and 5200 d) model: the peak at 44.3 d is due to the third planet; (ii) with respect to the resulting 3-planet model (other major peaks are aliases); (iii) with respect to the 4-planet model (2.8, 14.7, 44.3, and 5200 d); the peak marked is due to the fifth planet (the other major peak is an alias). Right: periodicity of the fifth planet, after subtracting the other planets. From Fischer et al. (2008, Figures 1–4, 8), by permission of IOP Publishing/AAS.

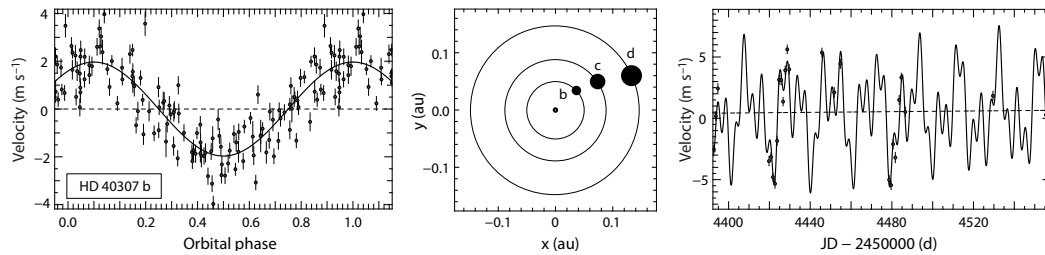


Figure 2.24: The ‘three super-Earth’ system HD 40307, observed with HARPS. Left: phase-folded velocities and Keplerian curve for the lowest mass planet b, after correction for the other two planets. Middle: pole-on view of the orbits; planet size is proportional to mass. Right: measured velocities with the three Keplerian model superimposed. From Mayor et al. (2009b, Figures 2–4), reproduced with permission © ESO.

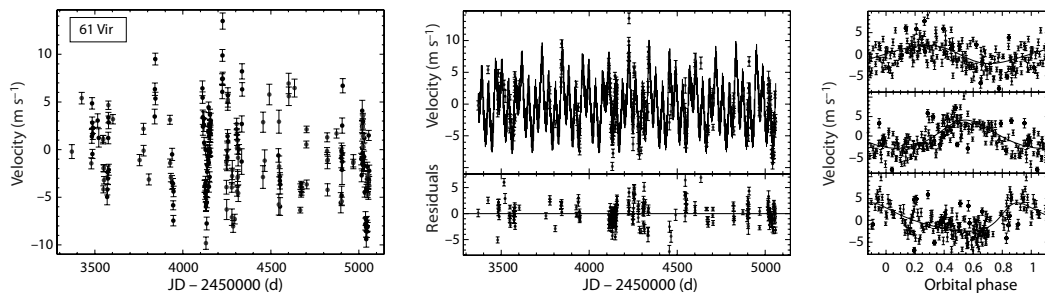


Figure 2.25: The ‘super-Earth and two Neptune’ system 61 Vir, observed with Keck and AAT. Left: relative radial velocities. Middle: observed velocities, and the three-planet model fit (residuals below). Right: modeled contributions from the three planets b–d (top to bottom;  $e = 0.1, 0.14, 0.35$  respectively). From Vogt et al. (2010b, Figures 2, 6–7), by permission of IOP Publishing/AAS.



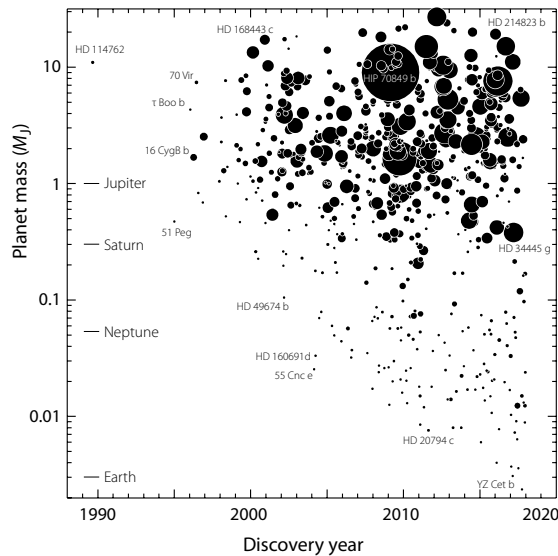


Figure 2.26: Planets discovered by radial velocity measurements, according to mass versus year of discovery. Data are for the 654 planets from the NASA Exoplanet Archive, 2017 December 31. Circle sizes are proportional to semi-major axis. The figure shows the decreasing mass detection limit with time, and the increase in semi-major axis orbits as the temporal baseline increases. Within a calendar year, discovery dates are random.

analyses of the planetary population are becoming possible, with statistically distinct properties and correlations becoming evident through principal component or hierarchical clustering analyses (e.g. Marchi, 2007).

#### 2.7.4 Reviews

Various reviews of radial velocity instrumentation, modeling, noise sources, discoveries, and findings have been made as the field has advanced (e.g. Marcy et al., 2006; Udry & Santos, 2007; Marcy et al., 2008; Santos, 2008; Johnson, 2009; Mayor et al., 2014; Pepe et al., 2014a; Panchuk et al., 2015; Hatzes, 2016a,b; Díaz, 2018; Figueira, 2018; Oshagh, 2018).

#### 2.7.5 On-line compilations

There are numerous on-line resources and compilations related to exoplanet surveys and results. The following (cf. Table 1.4) are particularly useful in the context of radial velocity exoplanet detections, since they maintain up-to-date records of new discoveries, compilations of related parameters, and a variety of tools for their inspection and analysis: (a) the NASA Exoplanet Archive; (b) the Extrasolar Planets Encyclopaedia, which is a compilation of exoplanet announcements, data, and bibliography, maintained by Jean Schneider at the Observatoire de Paris–Meudon; (c) the Exoplanet Orbit Database, which includes results from radial velocity

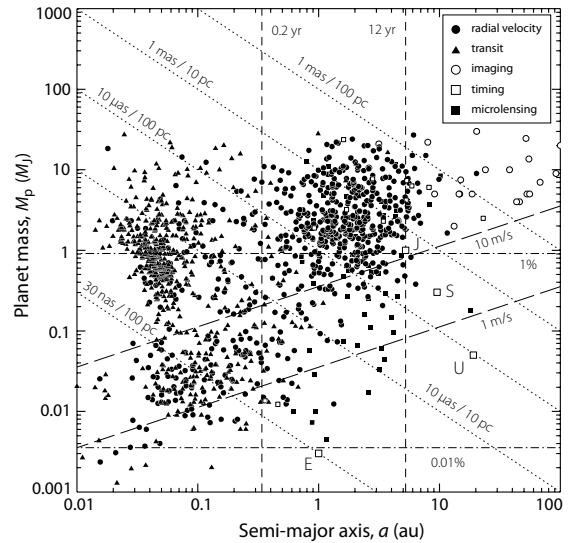


Figure 2.27: Detection domains based on orbital motion, with imaging and microlensing discoveries included. Masses are  $M_p \sin i$  for radial velocity discoveries. Lines from top left to bottom right show astrometric signatures of 1 mas and 10  $\mu$ as at distances of 10 and 100 pc (Equation 3.1, assuming  $M_\star = M_\odot$ ). Short- and long-periods cannot be detected by Gaia astrometry: vertical lines show limits at  $P = 0.2$  and 12 yr. Lines from top right to bottom left show radial velocity semi-amplitudes of  $K = 10$  and  $K = 1 \text{ m s}^{-1}$ . Horizontal lines are transit thresholds of 1% and 0.01%, corresponding to  $\sim 1R_J$  and  $\sim 1R_\oplus$  respectively. Positions of E(arth), (J)upiter, (S)aturn and (U)ranus are shown. Data from the NASA Exoplanet Archive, 2017 December 31.

and transit surveys for stars within 200 pc, aiming to incorporate the most secure spectroscopically-measured orbital parameters. It updates the Catalogue of Nearby Exoplanets (Butler et al., 2006b; Jones et al., 2008a), and is maintained by Jason Wright.

## 2.8 Surveys according to stellar type

For the reasons noted below, most early Doppler planet searches concentrated on G and K main sequence stars (dwarfs), in the mass range  $\sim 0.7 - 1.3M_\odot$ . Observing programmes progressively expanded to cover most late-type main sequence stars brighter than  $V \sim 7.5 - 8.5$  mag in a systematic manner, with others subsequently focusing on giants, M dwarfs, young stars, stars in clusters, and others. A compilation is given in Table 2.6.

An overview of the various surveys as a function of stellar class or category, and present results, are given in this and subsequent sections. Multiple planet systems are considered in Section 2.12, and planets around binary and multiple stars in Section 2.13.

### 2.8.1 Main sequence stars

G and K main sequence stars were the primary targets for the early radial velocity surveys. They have nu-

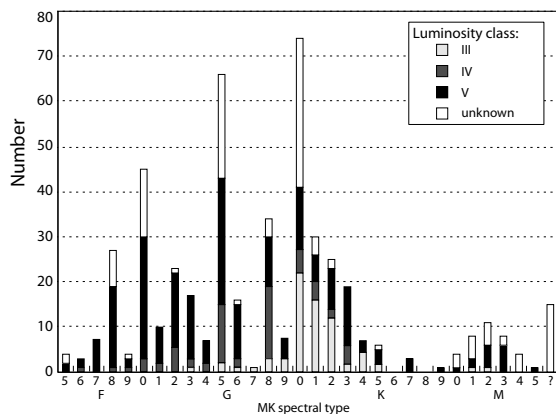


Figure 2.28: Radial velocity discoveries as a function of spectral type and luminosity class. Data, for 481 planet hosts, are from the NASA Exoplanet Archive, 2017 December 31. For 15 hosts, no spectral type is specified (box at far right). For more than 100 additional stars, no luminosity class is specified (unshaded).

merous absorption lines, are relatively bright, are relatively slow rotators with low rotational broadening, and have relatively stable atmospheres, with photometric jitter for inactive G dwarfs extending down to 2–3  $\text{m s}^{-1}$  (Table 2.1). Early reviews of these radial velocity searches were given by Latham (1997); Butler & Marcy (1998); Latham et al. (1998); Marcy & Butler (1998b); Nelson & Angel (1998); and Marcy & Butler (2000).

Of the larger survey programmes, CORALIE and HARPS are now surveying about 1600 stars in the southern hemisphere (Tamuz et al., 2008). The Anglo-Australian Planet Search has been in operation since 1998 (Tinney et al., 2001).

In the northern hemisphere, the ELODIE survey of more than 1000 targets originally focused on metal-rich stars (e.g. da Silva et al., 2006, 2007). ELODIE was replaced by SOPHIE in 2006, and the same programme has continued under the SOPHIE exoplanet consortium (e.g. Santos et al., 2008).

The Lick Planet Search programme began in 1987 when the first spectrum of  $\tau$  Cet was taken with an iodine cell and the Hamilton Spectrograph. Upgrades to the instrument improved the Doppler precision from about  $10 \text{ m s}^{-1}$  in 1992 to about  $3 \text{ m s}^{-1}$  in 1995. The project detected dozens of exoplanets with orbital periods ranging from a few days to several years. The Lick survey identified the first planet in an eccentric orbit (70 Vir), and the first multi-planet system around a normal main sequence star ( $v$  And). The Lick Planet Search with the Hamilton Spectrograph effectively ended when a heater malfunction compromised the integrity of the iodine cell. More than 14 000 velocities for 386 stars were obtained between 1987–2011 (Fischer et al., 2014).

The California & Carnegie search program uses the Keck, Lick, and AAT telescopes to survey about 1000

stars in the north and south (Valenti & Fischer, 2005).

The N2K consortium is using the Keck, Magellan, and Subaru telescopes to survey the ‘next 2000’ stars (Fischer et al., 2005; López-Morales et al., 2008). Estimates of  $T_{\text{eff}}$ ,  $[\text{Fe}/\text{H}]$ , and binarity were constructed from a starting list of more than 100 000 FGK dwarfs (Ammons et al., 2006; Robinson et al., 2006b). Their primary target list was then constructed from the more than 14 000 main sequence and subgiant stars with  $d < 110 \text{ pc}$ ,  $V < 10.5$  and  $0.4 < B - V < 1.2$ . Their final selection of 2000 stars was also biased towards higher metallicity targets, using broad-band photometry to define a subset with  $[\text{Fe}/\text{H}] > 0.1$ .

A large survey, of  $\sim 10\,000$  F8 and later dwarfs, started with the Sloan SDSS III MARVELS in 2008 (§2.6.7).

The Lick–Carnegie survey denotes the 20-year survey of FGKM dwarfs with Keck–HIRES. Butler et al. (2017) provide 60 949 precision velocities for 1624 stars, tabulating 357 significant periodic signals, of which 225 have been published as planet claims, 60 are classified as significant candidates awaiting photometric follow-up, and a further 54 requiring further confirmation. Candidates include a  $P = 9.9$ -d companion to the nearby Lalande 21185.

**Kinematics and chemistry** Adibekyan et al. (2013a) analysed the kinematics and chemical properties of 850 HARPS-observed FGK dwarfs in the solar neighbourhood ( $\log g \geq 4 \text{ dex}$ ;  $5000 < T_{\text{eff}} < 6500 \text{ K}$ ;  $-1.39 < [\text{Fe}/\text{H}] < 0.55 \text{ dex}$ ;  $d \leq 45 \text{ pc}$ ). Stars were assigned to the thin disk, thick disk and high- $\alpha$  metal-rich populations based on  $[\alpha/\text{Fe}]$  versus  $[\text{Fe}/\text{H}]$ .

They found a gradient of the rotational velocity of the thin disk stars with  $[\text{Fe}/\text{H}]$  of  $-17 \text{ km s}^{-1} \text{ dex}^{-1}$ , and a steep positive gradient for both thick disk and high- $\alpha$  metal-rich stars of  $+42 \text{ km s}^{-1} \text{ dex}^{-1}$ . There was no correlation between orbital eccentricities and metallicity for thin disk stars, but a steep negative gradient for both the thick disk and high- $\alpha$  metal-rich stars of  $-0.18 \text{ dex}^{-1}$ , in reasonable agreement with more distant SDSS stars (Lee et al., 2011d).

The results suggest that radial migration played an important role in the formation and evolution of the thin disk. For the thick disk stars, heating and migration (rather than accretion) could explain the steep positive gradient of  $V_{\phi}$  with  $[\text{Fe}/\text{H}]$ . The high- $\alpha$  metal-rich population shares properties of both the thin and thick disk populations, and comparison with stars from simulations including radial migration suggests that they may have originated from the inner Galaxy.

### 2.8.2 Early-type dwarfs

Observationally, radial velocity measures for higher mass main sequence stars (A–F spectral type) are complicated by three effects: a smaller number of spectral

Table 2.6: Radial velocity surveys focusing on particular stellar types. Surveys, instruments, and descriptions evolve with time, so the table is indicative rather than definitive. References describe the sample or more recent global results. Listings are chronological in survey start date within each category, and there is often overlap between some categories.

Selection	Telescope/instrument	N(stars)	Start	Reference
<b>Main sequence:</b>				
F8–M5	ESO–CES [ended 1998]	37	1992	Endl et al. (2002); Zechmeister et al. (2013)
GK, $V < 7.65$ , $v \sin i < 5 \text{ km s}^{-1}$	OHP–ELODIE	324	1994	Queloz et al. (2001)
FGKM (California–Carnegie)	Keck+Lick+AAT	1040	1995	Valenti & Fischer (2005)
FGK	Lick–Hamilton	107	1995	Marcy & Butler (1998a)
F7–M5, $< 50 \text{ pc}$	Keck–HIRES	530	1996	Vogt et al. (2000)
FGKM	Lick+Keck	844	1998	Nidever et al. (2002)
FGK IV–V, $V < 8$ , $\delta < -20^\circ$	AAT–UCLES	300	1998	Jones et al. (2002a)
F–M, metal-rich	AAT–UCLES	20	1999	Tinney et al. (2003b)
metal-poor	Keck–HIRES	200	2003	Sozzetti et al. (2006a, 2009b)
metal-poor	HARPS	104	2003	Santos et al. (2007, 2011)
F–M (N2K), metal-rich	Keck+Magellan+Subaru	2000	2004	Fischer et al. (2005, 2007a)
early-type, B8–F7	ELODIE/SOPHIE+HARPS	185	2004	Desort et al. (2009b)
metal-rich, Hipparcos-based	OHP–ELODIE/SOPHIE	1061	2004	da Silva et al. (2006)
F stars	Tautenburg	–	2005	Hartmann et al. (2010)
low activity (Rocky Planet)	AAT–AAPS	55	2007	O’Toole et al. (2009b,a)
metal-rich (Calan–Hertfordshire)	ESO–HARPS (CHEPS)	350	2008	Jenkins et al. (2009a, 2013a)
F8 and later	SDSS III MARVELS	10 000	2008	Ge et al. (2009)
metal-poor	FEROS	70	2008	Setiawan et al. (2010)
FGK, metal poor	ESO–HARPS	–	2010	Santos et al. (2014)
<b>Distance-limited samples:</b>				
distance-limited, $d < 50 \text{ pc}$	La Silla–CORALIE	1650	1998	Udry et al. (2000); Tamuz et al. (2008)
FGK distance-limited, $d < 57.5 \text{ pc}$	ESO–HARPS	850	2008	Lo Curto et al. (2010); Sousa et al. (2011b)
GKM (Eta–Earth)	Keck–HIRES	230	2008	Howard et al. (2009, 2011a,b, 2014)
<b>Solar twins and Jupiter analogues:</b>				
solar twins	ESO–HARPS	88	2010	Ramírez et al. (2014c)
Jupiter analogues	AAT	–	2011	Wittenmyer et al. (2011c, 2013b, 2014a, 2016a)
Jupiter analogues	SOPHIE	–	2012	Boisse et al. (2012b)
Jupiter analogues	HARPS	–	2012	Zechmeister et al. (2013)
<b>M dwarfs:</b>				
M2–M5, $V < 11.5$	Mt Wilson 2.5-m	65	1984	Marcy et al. (1986)
Lick/Keck	Lick+Keck	24	1994	Marcy et al. (1998)
$V < 7.5$	AAT–UCLES	7	1998	Jones et al. (2002a)
CNS3, $d < 9 \text{ pc}$ , $V < 15$	OHP–ELODIE/SOPHIE (N)	127	1995	Delfosse et al. (1999a)
" $d < 12 \text{ pc}$	La Silla–FEROS (S)	200	2000	Bonfils et al. (2004)
ESO survey	VLT–UVES	40	2000	Zechmeister et al. (2009)
"	VLT–UVES	26	2002	Guenther & Wuchterl (2003)
McDonald survey	HET–HRS+HJS	100	2002	Endl et al. (2003)
$d < 11 \text{ pc}$	HARPS	200	2003	Mayor et al. (2009a); Bonfils et al. (2013a)
ultracool (late M and L)	Keck–II NIRSPEC	59	2004	Blake et al. (2010)
Palomar	Palomar–TED1	100	2007	Edelstein et al. (2007)
K–M (M2K)	Keck	1600	2009	Apps et al. (2010); Fischer et al. (2012a)
M5–M9 (ROPS)	Magellan–MIKE	7	2012	Barnes et al. (2012)
M dwarfs (optical+infrared)	CAHA–CARMENES	300	2016	Quirrenbach et al. (2014)
<b>Subgiants:</b>				
subgiants	Lick+Keck	159	2006	Johnson et al. (2006b, 2010c, 2011a)
subgiants/giants	AAT–UCLES (Pan–Pacific)	170	2011	Wittenmyer et al. (2011a, 2016c,d)
<b>Giants:</b>				
G/K/clump giants	Lick+Keck	45	1999	Nidever et al. (2002)
"	Lick–CAT	179/373	1999	Hekker et al. (2006b); Quirrenbach et al. (2011c)
"	Okayama–HIDES/Subaru	300	2001	Sato et al. (2008a,b, 2010)
"	La Silla–FEROS	83	2001	Setiawan et al. (2003a,b)
" (in 13 open clusters)	HARPS	115	2003	Lovis & Mayor (2007)
" (Penn State/Torun)	HET–HRS	1000	2004	Gettel et al. (2012a); Niedzielski et al. (2016a)
"	Tautenburg 2-m	62	2004	Döllinger et al. (2007, 2009a)
"	BOA–Okayama	190	2005	Omiya et al. (2011)
"	SDSS III–MARVELS	1000	2008	Ge et al. (2009)
"	BOA–BOES	55	2010	Han et al. (2010)
"	La Silla–FEROS	166	2010	Jones et al. (2013b)

(continued over)

Table 2.6, continued.

Selection	Telescope/instrument	N(stars)	Start	Reference
Open clusters:				
Hyades giants	Okayama–HIDES	4	2001	Sato et al. (2007)
Hyades dwarfs	Keck+others	94	2002	Cochran et al. (2002)
13 clusters	CORALIE+HARPS	115	2003	Lovis & Mayor (2007)
M67	HARPS	88	2003	Pasquini et al. (2012); Brucalassi et al. (2014)
Praesepe	TRES	53	2012	Quinn et al. (2012b)
Young stars:				
young stars, Cha I cloud	VLT–UVES	12	2000	Joergens (2006)
young stars, 1–100 Myr	FEROS+HARPS	200	2003	Setiawan et al. (2008a,b)
$\beta$ Pic/TW Hya associations	Keck+NIRSPEC	20	2010	Bailey et al. (2012)
young associations (8–300 Myr)	HARPS	26	2010	Lagrange et al. (2013)
T Tauri	IRTF–CSHELL	9	2010	Crockett et al. (2012)
Binary and multiple stars:				
CORAVEL single-lined (SB1)	ELODIE+CORALIE	101	2001	Eggenberger (2010)
wide binaries, $a = 100 - 1000$ au	TNG–SARG	100	2003	Gratton et al. (2003)
binary/multiple	Keck–HIRES/HET–HRS	450	2003	Konacki (2005a,b)
visual binaries	Okayama–HIDES	9	2004	Toyota et al. (2009)

lines due to higher surface temperatures; line broadening due to higher rotational velocities, of order  $v \sin i \approx 100 - 200 \text{ km s}^{-1}$  for A-type stars (Galland et al., 2005a); and large atmospheric ‘jitter’ due to higher surface inhomogeneities and pulsation, of as much as  $50 \text{ m s}^{-1}$  or more for mid-F stars (Saar et al., 1998, see also Table 2.1). Together, these limit the applicability of the basic cross-correlation method (Griffin et al., 2000).

Chelli (2000) considered cross-correlation in Fourier space, which allows enhanced suppression of high-frequency noise and low-frequency continuum variations. The correlation is made between each spectrum of the target star and a reference spectrum specific to that star constructed from the sum of all the available spectra. When applied to early-type stars (Galland et al., 2005a), it suggested improved detection possibilities: for example, reaching the planetary domain with ELODIE for A-type main sequence stars with  $v \sin i$  up to  $100 \text{ km s}^{-1}$  for  $P < 10$  d, and for all A and F-type stars with HARPS, even for large  $v \sin i$  (Figure 2.29).

The resulting search for a sample of A–F main sequence stars, with ELODIE/SOPHIE in the north, and HARPS in the south, led to the first detection of a  $9.1 M_J$  companion around the F6V star HD 33564 (Galland et al., 2005b), a  $25 M_J$  planet/brown dwarf in orbit around HD 180777, a pulsating A9 dwarf with a high rotation of  $v \sin i = 50 \text{ km s}^{-1}$  (Galland et al., 2006b), and a series of subsequent discoveries from the southern survey (Desort et al., 2009b, 2010, and references).

### 2.8.3 Evolved stars: subgiants and giants

Observational complications inherent to high-mass dwarfs can be somewhat circumvented by observing their counterparts which have evolved away from the main sequence. After main sequence hydrogen burning, radii expand and atmospheres cool, leading to an

increase in metal lines. Angular momentum loss as stars cross the subgiant branch results from a coupling of stellar winds to rotationally-generated magnetic fields (Gray & Nagar, 1985; Schrijver & Pols, 1993; do Nascimento et al., 2000). The combination of cooler atmospheres and smaller rotational broadening makes evolved stars well suited for precision radial velocity surveys.

**Subgiants** Subgiants offer a reasonably favourable region of the HR diagram for radial velocity searches, with low rotational velocities of order  $v \sin i \lesssim 5 \text{ km s}^{-1}$ , and reasonably low photometric jitter of around  $5 - 10 \text{ m s}^{-1}$  (Wright, 2005, see also Table 2.1). Surveys at Keck and Lick have been made around 150 subgiants, selected from Hipparcos according to  $V < 7.6$  mag,  $2 < M_V < 3.5$ , and  $0.55 < B - V < 1.0$  (Johnson et al., 2006b), and numerous planets have been reported (Johnson et al., 2007b; Johnson, 2008; Johnson et al., 2010b,c, 2011b; Harakawa et al., 2010). Some 70 radial velocity detected systems around luminosity class IV hosts were listed in the NASA Exoplanet Archive at the end of 2017.

**G and K giants** Various radial velocity surveys of G and/or K giants have been made (Table 2.6): at Lick (e.g. Frink et al., 2002; Nidever et al., 2002; Hekker et al., 2006b, 2008; Reffert et al., 2015; Trifonov et al., 2015); Okayama–HIDES and Subaru–HDS (e.g. Sato et al., 2003, 2005b, 2008a,b, 2010); La Silla–FEROS (Setiawan et al., 2003a,b, 2004; Jones et al., 2013b); CORALIE and HARPS (Lovis & Mayor, 2007); Tautenburg (Hatzes et al., 2005; Döllinger et al., 2007, 2009a); HET–HRS (Niedzielski et al., 2007; Niedzielski & Wolszczan, 2008; Nowak & Niedzielski, 2008; Niedzielski et al., 2009a,b); the Sloan SDSS III MARVELS survey of some 1000 GK giants (Ge et al., 2009); BOAO–BOES (Han et al., 2010; Lee et al., 2012b); and Penn State–Torún (Gettel et al., 2012a).

By 2008, nine (radial velocity detected) planets around stars with  $M \gtrsim 1.5 M_\odot$  had been reported (John-

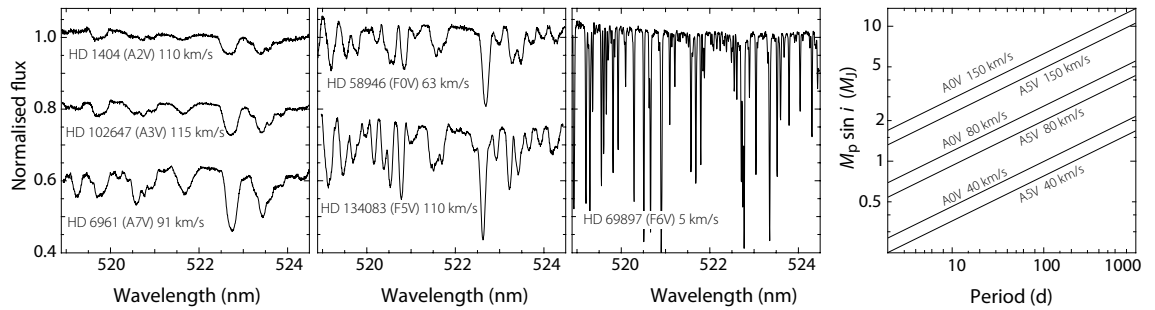


Figure 2.29: Left three panels: spectra of early-type stars acquired with ELODIE, showing the progression in both the number and the broadening of spectral lines for representative examples of A2V, A3V, A7V, F0V, F5V and F6V spectral types. Right: simulated mass detection limits for A-type stars observed with HARPS. From Galland et al. (2005a, Figures 1 and 10), reproduced with permission © ESO.

son, 2008), more than 40 by 2012 (Jones et al., 2013b; Refert et al., 2015), and some 90 by the end of 2017.

In contrast to main sequence stars, there is a lack of planets orbiting interior to  $\sim 0.6$  au (Figure 2.30). This may be the result of tidal interaction between the planet and the stellar envelope, such that planets orbiting interior to a certain distance would spiral inward to be engulfed by the host star (e.g. Siess & Livio, 1999b; Sato et al., 2008a; Villaver & Livio, 2009; Kunitomo et al., 2011). However, subgiants (of relatively smaller radii) show a similar trend, meaning that formation or migration effects, in addition to stellar evolution, may also be present (Johnson et al., 2007b; Bowler et al., 2010a).

#### 2.8.4 M dwarfs

**Motivation** Towards lower stellar masses, late K and M dwarfs are faint in the optical, such that high signal-to-noise spectra tend to be limited by telescope size. But they are important targets for exoplanet surveys because of their prevalence in the Galaxy (and therefore the large numbers which exist close to the Sun), and because differences in the number and type of exoplanets orbiting them reflect different conditions in the protoplanetary disks which provide additional constraints for planet formation theories.

Since they are brighter in the infrared, the development of near-infrared spectroscopy (§2.6.4) has intensified the interest in M dwarfs. Being less massive than GK dwarfs, the radial velocity amplitude is accentuated for a given planet mass (Equation 2.27). And being cooler, their habitable zones lie closer to the host star, such that habitable-zone planets are more easily detectable, and over shorter time spans (Reiners et al., 2010; Rodler et al., 2011).

**Surveys** As a consequence, numerous M dwarf radial velocity surveys have been initiated (Table 2.6). These started with the pioneering survey of 65 M dwarfs at the Mount Wilson 2.5-m telescope in 1984 (Marcy et al.,

1986). Radial velocity instruments incorporating programmes with a substantial focus on M dwarfs in the infrared are listed in Sections 2.6.4, 2.6.5, and 2.6.6.

The HARPS survey of 102 southern M dwarfs was carried out between 2003–2009 with radial velocities at the level of  $1\text{--}3\text{ m s}^{-1}$  (Bonfils et al., 2013a). The sample corresponds to a volume-limited list of M dwarfs with  $d < 11$  pc,  $\delta < +20^\circ$ ,  $V < 14$  mag, and  $v \sin i \leq 6.5\text{ km s}^{-1}$ , and is sensitive to a few Earth-mass planets for periods up to several hundred days.

The M2K programme (Apps et al., 2010; Fischer et al., 2012a) is a Doppler survey of M and K dwarfs selected from the SUPERBLINK proper motion survey (Lépine & Shara, 2005; Lépine & Gaidos, 2011), and set up to better understand the frequency and architectures of planetary systems around low mass stars.

The Red Optical Planet Survey was initiated with the Magellan 6.5-m and MIKE spectrograph, operating at  $0.5\text{--}0.9\ \mu\text{m}$  (Barnes et al., 2012). For 7 late-type M dwarfs (M5.5–M9), radial velocities at  $10\text{--}30\text{ m s}^{-1}$  accuracy suggest a habitable zone detection limit  $\sim 6M_\oplus$ .

The CARMENES survey of 300 M dwarfs has been assigned 600 nights at the CAHA 3.5-m telescope between 2016–18 (Quirrenbach et al., 2014; Alonso-Floriano et al., 2015). At  $1\text{ m s}^{-1}$  precision, goals are to detect  $2M_\oplus$  planets in the habitable zone at M5V, and  $\lesssim 5M_\oplus$  more generally. Simultaneous optical–infrared measurements should constrain effects of stellar activity.

**Massive planets** Microlensing surveys suggest that both ice and gas giant planets are common beyond the ice line (Gould et al., 2010b). However, the fraction of gas giant planets detected inside the ice line by Doppler surveys is relatively low for late K and early M dwarfs.

At the time when only 11 planets were known, Marcy et al. (1986) already concluded that gas giants occur less frequently around M dwarfs, a conclusion supported by later studies (Endl et al., 2003, 2006a; Butler et al., 2006a; Bonfils et al., 2007; Cumming et al., 2008).

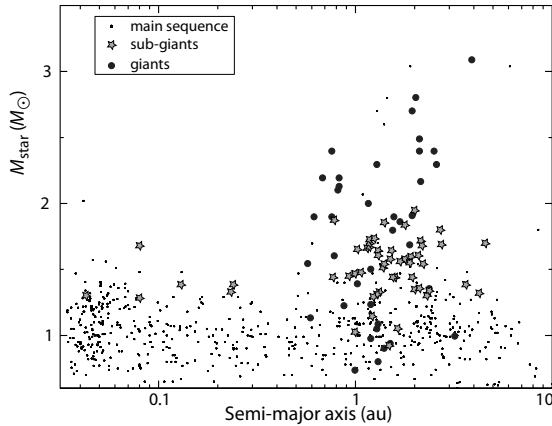


Figure 2.30: Semi-major axis distribution for planets around evolved stars, as of early 2013. Giants are indicated by filled circles, and subgiants by filled stars. For comparison, planets around main sequence stars are shown as small black circles. The giant star at  $a \sim 0.1$  au in the original figure corresponded to HIP 13044, which has since been retracted and therefore removed from this figure. From Jones et al. (2013b, Figure 1), reproduced with permission © ESO.

By late 2010, only seven Doppler-detected giant planets ( $M > 0.3M_J$ ) were known around six M dwarfs (Johnson et al., 2010d). These included GJ 317 of  $1.2M_J$  (Johnson et al., 2007a, Figure 2.31), and one of the most massive at  $2.1M_J$  around HIP 79431 (Apps et al., 2010).

Quantitatively, Endl et al. (2008a) estimated a 1.3% detection rate for Jovian-type planets at  $a < 1$  au earlier than M5V. Johnson et al. (2010d) estimated that  $3.4^{+2.2}_{-0.9}\%$  of stars with  $M_\star < 0.6M_\odot$  host planets with  $M \sin i > 0.3M_J$  and  $a < 2.5$  au. Restricted to metal-rich stars with  $[\text{Fe}/\text{H}] > +0.2$ , the occurrence rate rises to  $10.7^{+5.9}_{-4.2}\%$ . Bonfils et al. (2013a) found that giant planets ( $M_p \sin i = 100 - 1000M_\oplus$ ) have a low frequency ( $f \lesssim 0.01$  for  $P = 1 - 10$  d and  $f = 0.02^{+0.03}_{-0.01}$  for  $P = 10 - 100$  d). Santerne et al. (2016b) found an occurrence rate of giant planets with  $P < 400$  d of  $4.6 \pm 0.6\%$ .

**Lower-mass planets** At lower planetary masses, planets are common around M dwarfs. Bonfils et al. (2013a) found that super-Earths ( $M_p \sin i = 1 - 10M_\oplus$ ) appear to be very abundant, with  $f = 0.36^{+0.25}_{-0.10}$  for  $P = 1 - 10$  d and  $f = 0.35^{+0.45}_{-0.11}$  for  $P = 10 - 100$  d.

Kepler provides more robust statistics for lower mass planets, and also suggests that a reduced planet occurrence with later spectral type only applies to gas giants (Dressing & Charbonneau, 2013). Correcting for lower transit detection around higher mass stars with larger radii, Howard et al. (2012b) found that 20–30% of low-mass stars have planet candidates with Neptune-like radii between  $2 - 4R_\oplus$ , while the fraction of more easily detected Jupiter-radii planets remains at a few percent. Howard et al. (2012b) also observed a rising occurrence of small-radius planets among cooler, less massive stars.

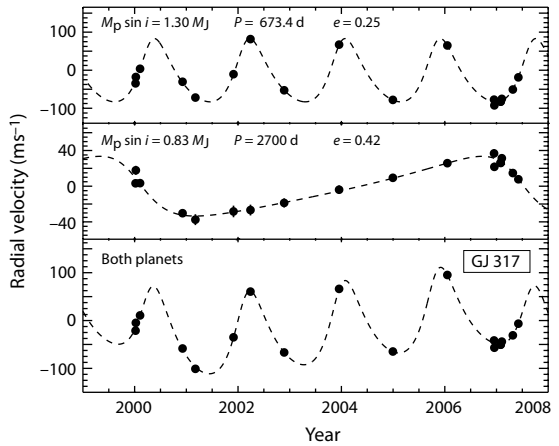


Figure 2.31: The M dwarf GJ 317, and the best-fitting two-planet model. The top two panels show the single-planet fits with the other component removed. Adding an outer planet with  $P \approx 2700$  d decreases the scatter of the residuals from  $12.5$  to  $6.32 \text{ m s}^{-1}$ , and the reduced  $\chi^2$  from 2.02 to 1.23. From Johnson et al. (2007a, Figure 4), by permission of IOP Publishing/AAS.

**Multi-planet systems** Latham et al. (2011) analysed multi-planet transiting systems detected with Kepler, and found that solar type and hotter stars are more common hosts of single transiting planets, while multi-planet systems are more often detected around cooler stars. Among the 170 multi-planet systems detected by Kepler, 78% contain planets no larger than Neptune, while close-in gas giant planets are far less common in multi-planet systems (Latham et al., 2011).

Further evidence of a high multiplicity of planets around low-mass stars was given by Anglada-Escudé et al. (2013a), who noted that there were three known systems with 3–4 planets around M dwarfs at the time (GJ 581, GJ 676A, and GJ 876), while only 12 M dwarfs were reported to have a single orbiting planet.

Of particular dynamical interest is GJ 876 (§2.12.4), with its two resonant Jovian-mass planets and an inner super-Earth (Rivera et al., 2005), and a fourth outer Uranus-mass planet in a Laplace resonance, with periods 30.4, 61.1, and 126 d (Rivera et al., 2010b).

**Metallicity effects** While the planet–metallicity correlation among solar-type stars is most evident for those hosting large-radius planets, a similar correlation for low-mass stars is significant even among hosts of small-radius planets (Schlaufman & Laughlin, 2011). Neves et al. (2013) used improved M dwarf metallicity estimates from HARPS ( $\sigma \sim 0.08$  dex) to confirm the correlation for giant planets, while for Neptune-mass and smaller hosts no significant correlation was found.

**Habitable zone planets** Over the planetary mass range  $1 \leq M \sin i \leq 10M_\oplus$ , the frequency of habitable-zone planets is  $0.41^{+0.54}_{-0.13}$  (Bonfils et al., 2013a).

## 2.9 Surveys according to other criteria

### 2.9.1 Nearby stars and volume-limited samples

**Eta–Earth survey** The Eta–Earth survey is a NASA–UC programme undertaken by the California Planet Search group with Keck–HIRES and targeting the nearest stars (the survey name reflects the notation assigned to the fraction of (Sun-like) stars that have at least one planet in the habitable zone,  $\eta_{\oplus}$ , §11.7.4). The target list is composed of 232 G, K, and M dwarfs (of which 66 are M dwarfs), being nearby ( $d < 25$  pc), bright ( $V < 11$ ), and with low chromospheric activity ( $R'_{\text{HK}} < -4.7$ ).

Eta–Earth has detected several low-mass planets (Howard et al., 2009, 2011a,b, 2014). It has also demonstrated that for G and K dwarfs the planet mass function rises steeply with decreasing planet mass, i.e. that small planets are common (Howard et al., 2010b).

**Volume-limited surveys** Volume-limited samples include the  $d < 50$  pc sample surveyed by Keck–HIRES (Vogt et al., 2000), and the  $d < 57.5$  pc sample surveyed by HARPS (Lo Curto et al., 2010; Sousa et al., 2011a). The latter includes a range of spectral types from M0–F2, with target stars known to have low levels of activity, low rotation rates, and to be free of known binaries and variable stars (Lo Curto et al., 2010; Sousa et al., 2011b). Samples have been selected on the basis of Hipparcos parallaxes, and will presumably be refined and extended with those from Gaia.

### 2.9.2 Specific nearby stars

Various nearby stars are now known to host planets, showing that even the immediate solar neighbourhood is rich in planetary systems.

Within 7 pc, radial velocity surveys have discovered gas giants orbiting  $\epsilon$  Eri (Hatzes et al., 2000), GJ 876 (Delfosse et al., 1998; Marcy et al., 1998), and GJ 832 (Bailey et al., 2009); intermediate mass planets (Neptunes and super-Earths) orbiting GJ 674 (Bonfils et al., 2007), GJ 876 (Rivera et al., 2010b), HD 20794 (Pepe et al., 2011), and GJ 581 (Mayor et al., 2009a), an approximately  $1 M_{\oplus}$  planet orbiting  $\alpha$  Cen B (Dumusque et al., 2012), and a  $5 M_{\oplus}$  planet orbiting GJ 15A (Howard et al., 2014).

Amongst the radial velocity detected planets, a number have attracted particular attention in view of their proximity to Earth, or their historical interest:

- *$\alpha$  Cen B*: an Earth-mass planet orbiting  $\alpha$  Cen B, a member of the closest stellar system to the Sun, with  $P = 3.236$  d and  $a = 0.04$  au, was reported from HARPS observations by Dumusque et al. (2012). This was subsequently considered controversial because of the presence of strong stellar activity (Hatzes, 2013b), and attributed to the artefacts of the window function (time sampling) in the original data (Rajpaul et al., 2016).
- *Barnard’s star*: the long controversy surrounding the possible existence of a planet around the M dwarf Barnard’s star (GJ 699), the second nearest star system to Earth (box, page 83), unless

essentially face-on, was emphatically concluded on the basis of HARPS observations by Anglada-Escudé et al. (2013a), and even more so with the 248 precise Doppler measurements obtained from Lick and Keck between 1987–2012 by Choi et al. (2013a). The latter found no significant periodic amplitudes above  $2 \text{ m s}^{-1}$ , setting upper limits on the minimum mass of any planets with orbital periods from 0.1–1000 d, excluding  $M_p \sin i > 2 M_{\oplus}$  and  $P < 10$  d, and  $M_p \sin i > 10 M_{\oplus}$  and  $P < 2$  yr.

- *Kapteyn’s star*: Kapteyn’s star is a low-metallicity M subdwarf, and the nearest halo object to the Sun. Its low metallicity and halo kinematics suggest an ancient origin, consistent with its low activity and slow rotation. Bayesian analysis of HARPS, HIRES, and PFS observations led to the announcement of two planets with periods of 48 and 120 d (Anglada-Escudé et al., 2014, the innermost within the habitable zone), raising questions about the system’s existence and survival given its halo origin and kinematic history. Robertson et al. (2015c) found that while the star is photometrically stable, spectral activity indices reveal a rotation  $P_{\text{rot}} = 143$  d, suggesting that the claimed planetary signal at an integer fraction (1/3) of the stellar rotation period is likely to be an artefact of stellar activity.

- *Proxima Cen*: at  $d = 1.295$  pc, the red dwarf Proxima Cen ( $\alpha$  Cen C) is the Sun’s closest stellar neighbour. From HARPS and VLT–UVES observations, Anglada-Escudé et al. (2016a) reported a terrestrial mass planet with  $M_p \sin i = 1.27 M_{\oplus}$  and  $P = 11.2$  d ( $a = 0.05$  au), and with an equilibrium temperature within the range where water could be liquid on its surface.

### 2.9.3 Solar twins and Jupiter analogues

**Solar twins** A survey of 88 stars considered as solar twins (§8.5.2) is being conducted with HARPS (Ramírez et al., 2014c), assisted by spectroscopy from Magellan–MIKE (Ramírez et al., 2014c).

**Jupiter analogues** In identifying systems which are most like the solar system, the presence of a Jupiter analogue, viz. a planet of Jupiter mass in a Jupiter-like orbit, may be a key ingredient (but see §12.2.2).

The high frequency of eccentric orbits amongst giant planets with semi-major axis  $a \gtrsim 1 - 2$  au suggests that common perturbation mechanisms may cause non-circular orbits both for the giant planets themselves, and for any lower mass rocky planets closer in. The eccentric giant planets tend to eject lower-mass objects, or enhance orbital eccentricities. Around solar-mass stars, analogues to Jupiter, both in terms of low eccentricity and comparable orbital semi-major axis, may therefore offer the best prospects for harbouring Earth-mass planets moving in circular orbits within the habitable zone.

One of the first such Jupiter analogues reported orbits the  $0.88 M_{\odot}$  star HD 154345 (Wright et al., 2007). With  $M_p \sin i = 0.92 M_J$ ,  $P = 9$  yr,  $a = 4.2$  au, and  $e = 0.16$ , the planet moves in a nearly circular orbit with no other giant planets lying inward of it. There may be additional planets with  $P = 45 - 60$  d, while the star itself has a heavy element abundance close to solar, with  $[\text{Fe}/\text{H}] = -0.10 \pm 0.04$  (Valenti & Fischer, 2005).

In around 2011, the Anglo–Australian Planet Search, in operation since 1998 (Tinney et al., 2001), shifted

its priority to the detection of Jupiter analogues. The observing strategy (Wittenmyer et al., 2013b) and target list were modified, with the aim of producing an accurate determination of their frequency (Wittenmyer et al., 2011c, 2013b, 2014a, 2016a). The modified target list includes stars with long-term velocity stability such that Jupiter analogues can be excluded (e.g. Wittenmyer et al., 2006), as well as those with incomplete orbits suggestive of long-period giants. Various candidates have been reported (Wittenmyer et al., 2011c, 2014a). Wittenmyer et al. (2011c) found that 3.3% of stars in their sample host Jupiter analogues. For 202 solar-type stars, Wittenmyer et al. (2016a) gave a frequency of  $6.8^{+2.8}_{-1.6}\%$  for  $a = 3 - 7$  au.

Other similar searches are also ongoing, with SOPHIE (Boisse et al., 2012b), with HARPS (Zechmeister et al., 2013), and as part of the Lick–Carnegie programme (Rowan et al., 2016).

**Sample results** By the end of 2012 this population of long-period Jupiter-mass planets numbered only around 20 candidates (Boisse et al., 2012b). Amongst their properties, there appears to be a fall-off in the mass–period distribution beyond  $\sim 4$  au (e.g. Boisse et al., 2012b, Figure 11), perhaps reflecting the decrease in frequency of giant planets at larger distance ( $\geq 5$  au) predicted by core accretion theories (Mordasini et al., 2012a). Those with a complete orbit are mostly of low eccentricity ( $e \lesssim 0.25$ ), while those with incomplete coverages are almost entirely eccentric ( $e \geq 0.25$ ), reflecting the expectation that eccentric orbits are more easily detected for periods longer than the observation times (Cumming, 2004).

Bryan et al. (2016b) used a Doppler survey at Keck combined with NIRC2 K-band adaptive optics imaging to search for massive, long-period companions to 123 systems with one or two planets previously detected from radial velocities. Sensitive to Jupiter-mass planets out to 20 au, they discovered eight new long-period planets, and 20 systems with statistically significant trends indicating the presence of an outer companion beyond 5 au. They reported a total occurrence rate of companions as  $52 \pm 5\%$  in the range  $1 - 20 M_J$  and  $5 - 20$  au, a declining frequency for gas giant planets beyond  $3 - 10$  au, that hot gas giants are more likely to have an outer companion than cold gas giants, and that planets with an outer companion have higher than average eccentricities than their single counterparts, suggesting that dynamical interactions between planets may play an important role.

Establishing whether these ‘Jupiter analogues’ represent planets which formed beyond the snow line and migrated inward as the protoplanetary disk dissipated, or whether their present orbits result from some contribution from planet-planet scattering, will require further study. Enlarged samples are expected as the duration of high-accuracy Doppler surveys continues, with a substantial harvest expected from the later Gaia astrometry data releases around 2020 (§3.9).

**Examples** In terms of its measured period and eccentricity (if not its mass, at  $M_p \sin i = 3.9 M_J$ ), 55 Cnc d is one of the closest Jupiter analogues discovered to date (Nelson et al., 2014b). Estimates of  $P = 4909 \pm 30$  d and  $e = 0.02 \pm 0.008$  by Endl et al. (2012), were revised to  $P = 4867$  d and  $e = 0.0269$  by Nelson et al. (2014b), compared to that of Jupiter, viz.  $P_J = 4333$  d and  $e_J = 0.049$ . A Jupiter twin around the solar twin HIP 11915 was reported by Bedell et al. (2015).

## 2.9.4 Effects of metallicity

**Host star metallicity** A correlation between the presence of gas giant planets and high metallicity of the host star was noted in the early years of exoplanet discoveries (Gonzalez, 1997). More homogeneous studies have confirmed the trend (e.g. Fischer & Valenti, 2005; Sousa et al., 2011b), with investigations extending to the abundances of numerous elements in addition to iron. The consensus is that the effect is attributable to primordial effects rather than to self-enrichment by accretion, and is considered further in §8.4. The correlation has been taken to imply that core accretion is a plausible mechanism for the formation of giant planets (§10.13.3), while it may also be consistent the formation by the tidal downsizing of giant planet embryos (§10.5.2).

The correlation between occurrence and metallicity may not extend to the lowest mass planets (Udry et al., 2006). A correlation for planets orbiting giants stars was not found by Pasquini et al. (2007), but was present in the sample of Reffert et al. (2015).

From their analysis of planet frequency as a function of  $[\text{Fe}/\text{H}]$ , Sousa et al. (2011b) derive a power-law fit, for masses in the range  $0.1 - 25 M_J$ , given by

$$P_{\text{planet}} = 0.038 \left[ \frac{\langle N_{\text{Fe}}/N_{\text{H}} \rangle}{\langle N_{\text{Fe}}/N_{\text{H}} \rangle} \right]^{2.58}. \quad (2.53)$$

Their large volume-limited sample with spectroscopic metallicities again confirms the correlation between planet frequency and host star metallicity, with stars of lower metallicity also hosting less massive planets.

**Metal-poor stars** The observed correlation between exoplanet occurrence and host star metallicity suggests that radial velocity searches around metal-poor stars should have relatively low success. Nonetheless, specific searches around low-metallicity stars have been targeted since 2003.

A HARPS survey down to  $[\text{Fe}/\text{H}] = -1.4$  found only three moderately metal-poor stars hosting giant planets with  $P > 700$  d (Santos et al., 2007, 2011). The frequency of super-Earths and Neptunes is  $\sim 13\%$ , comparable to that for solar-metallicity hosts (Faria et al., 2016b).

Keck–HIRES carried out a 3-year survey around 160 stars down to  $[\text{Fe}/\text{H}] = -2.0$ , finding only one (with  $[\text{Fe}/\text{H}] = -0.49$ ), and no evidence for giant planets within 2 au (Sozzetti et al., 2006a, 2009b).

FEROS observed 96 A and F stars in the range  $-4 < [\text{Fe}/\text{H}] < -0.5$  (Setiawan et al., 2010, 2012). Reports of the very low metallicity HIP 13044, a Galactic halo stream star with  $[\text{Fe}/\text{H}] = -2.0$  (Setiawan et al., 2010), and HIP 11952 with  $[\text{Fe}/\text{H}] = -1.8$  (Setiawan et al., 2012), have not been confirmed (see Appendix C).

As of the end of 2017, there are still only  $\sim 40$  planet hosts with  $[\text{Fe}/\text{H}] < -0.5$ , of which only 10 are radial velocity discoveries. The most extreme are the 2-



planet system BD+20 2457 with  $[\text{Fe}/\text{H}] = -1.00$  (Niedzielski et al., 2009b), Kapteyn's star (§2.9.2) with  $[\text{Fe}/\text{H}] = -0.89$  (Anglada-Escudé et al., 2014), and HD 114762 with  $[\text{Fe}/\text{H}] = -0.77$  (Latham et al., 1989; Kane et al., 2011c).

### 2.9.5 Open clusters

The determination of stellar masses for giant stars is complicated by the fact that evolutionary tracks for stars covering a wide range of masses converge to the same region of the Hertzsprung–Russell diagram. This consideration motivated Sato et al. (2007) and Lovis & Mayor (2007, 115 stars in 13 clusters) to target giants in intermediate-age (0.2–2 Gyr) open clusters, where cluster membership combined with the estimated cluster age provides a more secure estimate of the host star masses compared to that of field giants.

A number of planets orbiting stars in open clusters have now been discovered from radial velocity surveys (see Appendix C, where NGC and Pr(aesepe) members are classified explicitly), including:

*Hyades*: early observations of 94 main sequence stars yielded no close-in giant planets (Cochran et al., 2002; Paulson et al., 2002, 2003, 2004a,b). The first discoveries came with the  $7.6M_J$  planet orbiting the giant  $\epsilon$  Tau (Sato et al., 2007), and the cluster's first hot Jupiter, HD 285507 (Quinn et al., 2014).

*M67 (NGC 2682)*: Pasquini et al. (2012) reported 11 stars with variability which may indicate planet-hosting stars. A 7-yr programme to measure 88 main sequence and evolved stars in M67 (Pasquini et al., 2012; Brucalassi et al., 2016b, 2017) has discovered five 1-planet systems. Results yield a giant planet occurrence of  $18_{-8}^{+12}\%$  slightly higher but consistent with that of field stars, but with a substantially higher rate of cluster hot Jupiters,  $5.7_{-3.0}^{+5.5}\%$  (Brucalassi et al., 2017).

*Praesepe*: Quinn et al. (2012b) reported the discovery of two giant planets amongst 53 single members surveyed in this metal-rich open cluster, Pr 201 b and Pr 211 b (the latter now known to be multiple, Malavolta et al. 2016). These represented the first known hot Jupiters in an open cluster, and the first known to orbit Sun-like, main-sequence cluster stars, providing a lower limit of  $3.8_{-2.4}^{+5.0}\%$  on the hot Jupiter frequency in this cluster.

*Others*: two massive planets ( $10.6$  and  $19.8M_J$ ) were reported around giants in the open clusters NGC 2423 and NGC 4349 respectively (Lovis & Mayor, 2007).

### 2.9.6 Young stars and associations

While there is a consensus that planets form from the gas and dust disks around young stars, details of their early formation, including the time scale of planet formation, remain unclear. Observationally, radial velocity detection around young stars is hampered by increased host star activity, and planet discoveries in systems with disks have typically derived from direct imaging.

**Young stars** Searches for planets around young stars with protoplanetary disks, of age 1–100 Myr, have been targeted by FEROS/HARPS (Setiawan et al., 2008a). Discoveries include a  $6.1M_J$  planet around HD 70573, a 100 Myr GV star (Setiawan et al., 2007), and a  $9.8M_J$  planet around TW Hya, a young (8–10 Myr) star surrounded by a prominent circumstellar disk (Setiawan et al., 2008a). The planet orbits the star with  $P = 3.56$  d ( $a = 0.04$  au), inside the inner rim of the disk, perhaps demonstrating that planets can form before the disk has been dissipated by stellar winds and radiation. CI Tau is a (candidate)  $P = 9$ -d  $10M_J$  planet orbiting a 2 Myr old classical T Tauri star still possessing a protoplanetary disk (Johns-Krull et al., 2016a; Rosotti et al., 2017).

Jeffers et al. (2014) estimated detection prospects around young active G and K dwarfs. Models of stellar activity were based on tomographic imaging of the G dwarf HD 141943 and the K1 dwarf AB Dor, including contributions from plages and star spots. They showed that increased stellar activity in young solar-type stars strongly impacts the detection of Earth- and Jupiter-mass planets, and that the degree of activity jitter is directly correlated with stellar  $\nu \sin i$ . They concluded that close-in Jupiter-mass planets can be detected around fast-rotating young active stars, Neptune-mass planets around moderate rotators, while super-Earths are only detectable around very slowly rotating stars.

**Associations** In the  $\beta$  Pic and TW Hya associations, monitoring by Keck–NIRSPEC of 20 young stars excluded the presence of any hot ( $P < 3$  d) companions more massive than  $8M_J$  and any ‘warm’ ( $P < 30$  d) companions more massive than  $17M_J$  (Bailey et al., 2012).

A survey of pre-main sequence (T Tauri) stars in Taurus–Auriga was reported by Crockett et al. (2012). Strong magnetic fields gives rise to large cool star spots, which can mimic a radial velocity modulation, with simultaneous observations at 670 nm and  $2.3 \mu\text{m}$  used to constrain the nature of the signals.

A HARPS survey of 26 A–K stars in nearby young (8–300 Myr) associations yielded no planets (Lagrange et al., 2013). Their technique should allow the detection of planets less massive than Jupiter, reaching a few Neptune masses around young stars with ages  $\geq 30$  Myr.

### 2.9.7 Follow-up of transit candidates

Verification of candidate transiting planets typically involves follow-up radial velocity observations, although less direct validation techniques are adopted for host stars too faint for such observations (§6.12.5).

Amongst numerous such efforts required in vetting the large numbers of accessible (brighter) Kepler candidates, and by way of illustration only, many have been confirmed with OHP–SOPHIE (e.g. Ehrenreich et al., 2011a; Santerne et al., 2011b; Bouchy et al., 2011a; Santerne et al., 2011a; Bonomo et al., 2012b; Santerne et al.,

2012b,a; Díaz et al., 2013; Moutou et al., 2013a; Barros et al., 2014b; Deleuil et al., 2014; Santerne et al., 2014; Díaz et al., 2014b; Bruno et al., 2015; Almenara et al., 2015b; Bourrier et al., 2015a). Orbital parameters for 231 transiting giant planets in 45 systems have been refined by HARPS-N over 3 years (Bonomo et al., 2017a).

**False-positive rate for Kepler close-in giants** From observations with OHP-SOPHIE, Santerne et al. (2012a) derived a false-positive rate for Kepler candidates with transit depth  $> 0.4\%$ ,  $P < 25$  d and brighter than 14.7 mag. Out of 46 candidates, they found five undiluted eclipsing binaries, two brown dwarfs, six diluted eclipsing binaries, and nine new transiting planets that complemented 11 already published. The remaining 13 candidates were not followed-up or remain unsolved due to photon noise limitation or lack of observations. From these results they computed the false-positive probability for Kepler close-in giant candidates to be  $35 \pm 6\%$ , compared with previous estimates of below 5%.

## 2.10 Masses and orbits

### 2.10.1 Mass distribution

Various distributions of the radial velocity planet population are shown in Figure 2.32. In the following discussions, it is recalled that for any individual object the measured mass is uncertain by the factor  $\sin i$ . Similarly, the underlying distribution of  $M_p$  (rather than that of the minimum mass  $M_p \sin i$ ) cannot be derived unambiguously (cf. Jorissen et al., 2001). For a random orientation of orbital planes,  $\langle M_p \rangle = (\pi/2) M_p \sin i$ .

### 2.10.2 Mass of host star

The results of the surveys of FGK main sequence stars in the mass range  $0.3 - 1.4 M_\odot$ , along with the few, typically low-mass planets detected around M dwarfs, and the more massive planets found from the evolved star surveys, suggest that the material trapped in the form of planets is strongly correlated with the mass of the primary star (e.g. Lovis & Mayor, 2007, their Figure 11).

If the surface density of disk material furthermore scales with the central star mass, there should be an additional correlation between planet occurrence and stellar mass (Laughlin et al., 2004a; Ida & Lin, 2005b; Kennedy & Kenyon, 2008b).

At higher stellar mass,  $M_\star \geq 1 M_\odot$ , the occurrence rate of giant planets for 373 G and K-type giant stars, measured at Lick over 12 years, was assessed by Reffert et al. (2015). They found strong evidence for a planet-metallicity correlation, in agreement with the findings for main-sequence stars. Planet occurrence increases in the interval  $1 - 1.9 M_\odot$ , with a maximum at  $\sim 1.9 M_\odot$ , and a rapidly falling occurrence beyond  $2.5 - 3.0 M_\odot$ , with no planets around stars  $\geq 2.7 M_\odot$ , albeit with 113 stars with  $2.7 - 5 M_\odot$  in their sample.

### 2.10.3 Period distribution

The significant numbers of giant planets with  $P \sim 3 - 10$  d ( $a \sim 0.05 - 0.1$  au), orbiting close to their host stars, was essentially unexpected before the early exoplanet discoveries.<sup>11</sup> The early trend has continued: some 30 radial velocity discoveries with  $M_p \sin i > 0.5 M_J$  have  $P < 10$  d. As discussed elsewhere, these ‘hot Jupiters’ are believed to have formed much further out, before being scattered or migrating inwards to their present location, with some mechanism halting the migration before the planets fall onto their host stars.

The observed masses and orbits of giant planets within 5 au are reproduced rather well by current theories of their formation and migration (Kley et al., 2005), including their dependence on stellar metallicity and mass (Ida & Lin, 2004b, 2005b; Armitage, 2007b).

The period distribution for  $P \geq 1000$  d ( $a \geq 2$  au) is less certain, with the apparent decline beyond 3 au probably largely attributable to the limited duration, of around 10 years, of the high-precision Doppler surveys (Kholshchevnikov & Kuznetsov, 2002). Some of the best constraints, out to some 8–10 au, come from the almost 30-yr baseline for 17 objects included in the early CFHT and McDonald Observatory observations (Wittenmyer et al., 2006, 2007). Extrapolation out to 20 au, comparable to the orbit of Uranus, is correspondingly uncertain, but even a flat extrapolation would approximately double the known rate (Marcy et al., 2005a). This suggests that a large population of still undetected Jupiter-mass planets may exist between 3–20 au, perhaps implying that as many as 20% of Sun-like stars have a giant planet within 20 au (Cumming et al., 2008).

Adaptive optics imaging targeting the detection of giant planets around young stars from their thermal infrared emission using Gemini-Altair (Lafrenière et al., 2007a) and VLT-NACO (Apai et al., 2008) has yielded independent limits on their occurrence, also suggesting a decreasing number beyond 20–30 au.

Current theories support the idea that gas giants may be rare beyond 20 au. The declining densities of protoplanetary disks with increasing radius, combined with the longer dynamical time scales, together imply a longer time scale for planetary growth compared with protoplanetary disk lifetimes of order 3 Myr (Alibert et al., 2005a; Hubickyj et al., 2004).

**Mass-period relation** A correlation is seen between  $M_p$  and  $a$  (Figure 2.32b). There is a paucity of massive planets on short-period orbits (Zucker & Mazeh, 2002; Udry et al., 2002; Jiang et al., 2007). There is also a rise in

<sup>11</sup> Although Struve (1952), in considering the timeliness of radial velocity searches, commented that ‘It is not unreasonable that a planet might exist at a distance of  $1/50$  au... Its period around a star of solar mass would then be about 1 day.’

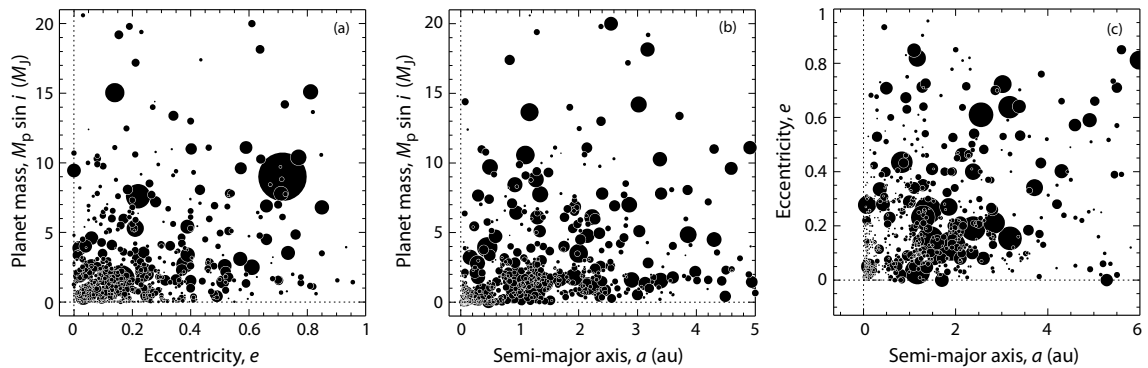


Figure 2.32: Properties of the radial velocity planets: (a) planet mass  $M_p \sin i$  versus eccentricity  $e$ , with circle sizes proportional to  $a$ ; (b) planet mass  $M_p \sin i$  versus semi-major axis  $a$ , with circle sizes proportional to  $e$ ; (c) eccentricity  $e$  versus semi-major axis  $a$ , with circle sizes proportional to  $M_p \sin i$ . Data are from the NASA Data Archive, 2017 December 31.

the maximum planet mass with increasing  $a$  (Udry et al., 2003c). Since more massive planets are presumably formed further out in the protoplanetary disk, where accretion material is abundant and orbital paths longer, the larger masses are perhaps less easily displaced by whatever migration mechanism forces them inward.

#### 2.10.4 Eccentricities

Most pre-discovery theories of planetary formation suggested that exoplanets would be in circular orbits similar to those in the solar system (Boss, 1995; Lissauer, 1995). In practice (Figure 2.32), there is a significant correlation between  $a$  (or  $P$ ) and  $e$  (Stepinski & Black, 2000). Close-in planets are in preferentially low eccentricity orbits, while exoplanets with  $P \geq 6$  d have  $e$  spanning the range 0–0.93, with a median  $e \sim 0.3$ . A few, long-period, low-eccentricity orbits are found, representing a small sample of solar system analogues.

As discussed elsewhere, the origin of the eccentric orbits probably arises from several mechanisms: gravitational interaction between multiple giant planets; interaction between the giant planets and planetesimals in the early stages of planet formation; or the secular influence of an additional passing mass, either unbound or bound (with the four most extreme eccentricities being found orbiting components of binary systems). Furthermore, for small pericentre distances, tidal circularisation appears to be an important damping mechanism.

With significant numbers of exoplanets now characterised, observed eccentricities can impose an informative prior on their distribution (e.g. Hogg et al., 2010; Savransky et al., 2011; Wang & Ford, 2011; Zakamska et al., 2011; Kipping, 2013b; Lucy, 2013; Wittenmyer et al., 2013c; Limbach & Turner, 2015). There are situations, as in the simulations of astrometric orbit detection with Gaia (Perryman et al., 2014a, see also §3.9), where this knowledge can provide a useful constraint,

rather than assuming (say) a uniform prior over the range  $0 \leq e < 1$ .

Some authors (e.g. Steffen et al., 2010; Wang & Ford, 2011; Kipping et al., 2012b) have adopted a combination of a Rayleigh distribution (to reflect the effects of planet–planet scattering) and an exponential distribution (to reflect the effects of tidal dissipation).

Zakamska et al. (2011, their Figure 12) determined an intrinsic (de-biased) eccentricity distribution from the radial velocity detection sample of Butler et al. (2006b), representing the sum of two populations: one on circular orbits (38% of all planets) and the remaining a ‘dynamically active’ distribution with eccentricities following the form of Jurić & Tremaine (2008)

$$\frac{dN_{\text{pl}}}{de} \propto e \exp \left[ -\frac{1}{2} \left( \frac{e}{0.3} \right)^2 \right]. \quad (2.54)$$

Kipping (2013b) proposed the Beta distribution

$$P_{\beta}(e; a, b) \propto e^{a-1} (1-e)^{b-1}, \quad (2.55)$$

which can replicate a wide and diverse range of probability distributions. Regression of the cumulative density function of  $e$  from radial velocity detected planets, suggests that  $a = 0.867 \pm 0.044$  and  $b = 3.03 \pm 0.17$  provide a good fit to the observed distribution (Figure 2.33). Furthermore, short-period planets have a higher proportion of low- $e$  orbits than long-period planets (Figure 2.34), consistent with tidal circularisation.

**Correlation of eccentricity with multiplicity** The known population of exoplanets exhibits a much wider range of orbital eccentricities than the planets of the solar system, with a much higher average eccentricity.

From radial velocity surveys, Jurić & Tremaine (2008) and Rodigas & Hinz (2009) noted that eccentricities in 2-planet systems tend to be lower than in single-planet systems. From 403 (of 441 known) radial velocity planets, including 127 in multi-planet systems with multiplicities up to six, Limbach & Turner (2015) noted an

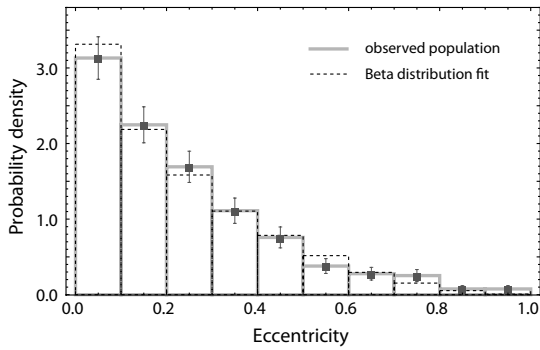


Figure 2.33: Probability density distribution of  $e$  for 396 exoplanets (black bars), from [www.exoplanets.org](http://www.exoplanets.org). The solid histogram is the observed sample, with errors from Poisson statistics. The dashed histogram is the probability density function of a synthetic population generated using the maximum likelihood parameters of a Beta distribution regressed to the observed sample. Using just two shape parameters, the fitted Beta distribution is consistent with the observed distribution. From Kipping (2013b, Figure 3), © Oxford University Press.

anti-correlation of eccentricity with multiplicity. Specifically, as the multiplicity increases, the eccentricity decreases as a power law of index  $-1.20$  (Figure 2.35). Mean and medians of the solar system planets fits an extrapolation to the 8-planet case rather precisely. Similar results are found for transiting systems (§6.30.3).

The model of Limbach & Turner (2015) implies that  $\sim 80\%$  of their 1-planet and 25% of their 2-planet systems have additional, as yet undiscovered, members. They also concluded that the low solar system eccentricities are not anomalous when accounting for multiplicity (as confirmed by Xie et al., 2016) and that, if low eccentricities favour high multiplicities, habitability may be more common in higher-multiplicity systems.

### 2.10.5 Brown dwarf desert

Due to the large reflex motion they induce in their host stars, early radial velocity surveys were expected to discover brown dwarf companions to solar-type stars with relative ease. Their frequency and orbits would provide observational constraints on theories of formation and evolution of both planets and brown dwarfs.

A prominent feature of the early radial velocity exoplanet discoveries, in contrast, was the general absence of close-in ( $a < 3 - 4$  au) substellar objects with masses in the range  $10 - 80 M_J$ , a paucity referred to as the *brown dwarf desert* (Marcy & Butler, 2000).

Subsequent radial velocity surveys of several thousand stars (including those of SDSS APOGEE and MARVELS, §9.2.2) have confirmed this pattern, finding brown dwarf companions out to  $P \sim 10$  yr, but yielding only a small number in the mass and separation range characterising the ‘desert’ (e.g. Grether & Lineweaver,

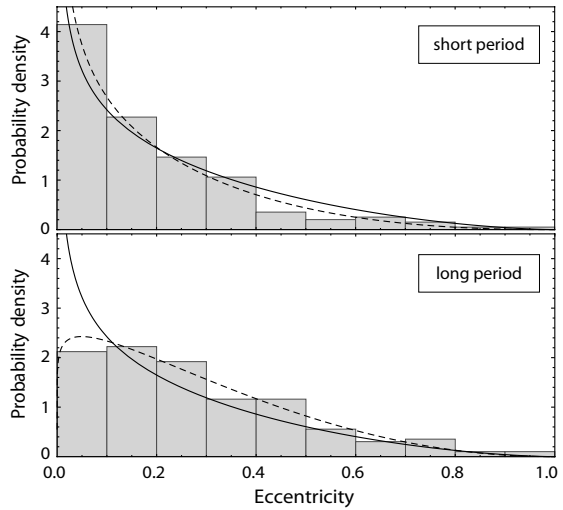


Figure 2.34: Probability density function for short-period (top) and long-period planets (bottom) from [www.exoplanets.org](http://www.exoplanets.org), divided at the median period of 382.3 d. The solid line is the regression of a single Beta distribution to both sets. The dashed line is the regression of two independent Beta distributions. From Kipping (2013b, Figure 4), © Oxford University Press.

2006; Sozzetti & Desidera, 2010; Sahlmann et al., 2011b; Ma & Ge, 2014; Bouchy et al., 2016; Santerne et al., 2016b; Troup et al., 2016; Wilson et al., 2016a; Borgniet et al., 2017; Grieves et al., 2017).

Of these, Sahlmann et al. (2011b) placed an upper limit of close ( $P \lesssim 300$  d) brown dwarf companions around solar-type stars of 0.3–0.6%. Grether & Lineweaver (2006) found that  $\sim 16\%$  of solar-type stars have close ( $P < 5$  yr) companions with  $M_p > 1 M_J$ , but only  $< 1\%$  are brown dwarfs. The minimum number of companions per unit interval in log mass, or the ‘driest’ part of the desert, is at  $\sim 30 - 55 M_J$  (Grether & Lineweaver, 2006; Ma & Ge, 2014). The ‘desert’ may be particularly pronounced for solar-mass stars (Duchêne & Kraus, 2013), and more populated for more massive hosts (Guillot et al., 2014b; Troup et al., 2016).

Díaz et al. (2012) aimed to improve statistical knowledge of their frequency in a sample of northern hemisphere stars observed with OHP-SOPHIE. Their improved masses increased the number of substellar objects or candidates with  $M_p > 10 M_J$  orbiting solar-type stars in relatively short orbits. Mass and eccentricity distributions of the resulting 60 or so objects are shown in Figure 2.36. The full results of the programme, including occurrence rates, are pending (Wilson et al., 2016a).

Borgniet et al. (2017) derived consistent occurrence rates for AF-type stars: brown dwarf rates for  $P = 1 - 1000$  d of 2% and 3% for  $M_\star = 1.1 - 1.5 M_\odot$  and  $M_\star = 1.5 - 3 M_\odot$  respectively, and corresponding Jupiter-mass ( $1 - 13 M_J$ ) rates of 4% and 6% for  $P = 1 - 1000$  d, and 2% and 4% for  $P = 1 - 100$  d.

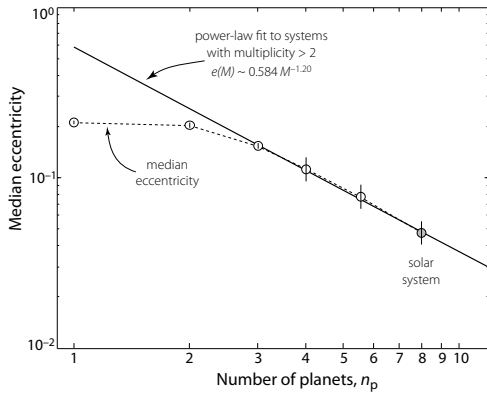


Figure 2.35: Power-law fit to median eccentricity in radial velocity systems with  $n_p > 2$ . The fit suggests that the 1- and 2-planet data are higher-multiplicity systems with undiscovered members. From *Limbach & Turner (2015, Figure 5)*, with permission ©(2015) National Academy of Sciences.

**Imaging and astrometry** Similar statistics follow from infrared coronagraphic searches at close separation (McCarthy & Zuckerman, 2004), and other imaging programmes (Kraus et al., 2011; Evans et al., 2012). The majority of those detected may be H-burning stars with low orbit inclination (Halbwachs et al., 2000; Udry et al., 2000). Other mass constraints have come from Hipparcos astrometry (Halbwachs et al., 2000). Greatly improved statistics can be expected from Gaia (§3.9), for which the brown dwarf desert occupies a region of pronounced astrometric sensitivity, and many thousands of desert occupants might be expected.

HST–NICMOS imaging of 255 stars in 201 systems within 10 pc, including 138 M dwarfs in 126 systems, suggests that the desert extends to binaries with low-mass primaries, and is largely independent of primary mass, mass ratio, and separation (Dieterich et al., 2012). At the same time, wide L and T dwarf companions from 2MASS and other near infrared surveys (§9.2.2) suggest that brown dwarfs may not be unusually rare as wide (> 1000 au) companions to F–M0 main sequence stars (Gizis et al., 2001; Grether & Lineweaver, 2006).

Similar low occurrence rates across a range of discovery methods underlines that the absence is not some artefact of the radial velocity method. As a corollary, the clear mass separation between stellar and planetary companions to solar-type stars renders exoplanets distinguishable by their high occurrence at low masses, irrespective of their actual values of  $\sin i$ .

**Examples** As of end 2017, there were some 60–70 known brown dwarf companions around solar-type stars (Ma & Ge, 2014; Grieves et al., 2017). Objects occupying the brown dwarf desert include the radial velocity discovery HD 137510, with  $M_p \sin i = 26 M_J$ ,  $e = 0.4$ ,  $P = 798$  d (Endl et al., 2004); the transiting CoRoT–3 b (Deleuil et al., 2008) and CoRoT–33 b (Csizmadia et al., 2015); the gravitational lens companion MOA–2007–BLG–197L b (Ranc et al., 2015); and various SDSS–III APOGEE (Troup et al., 2016), and MARVELS (Grieves et al., 2017) candidates.

**Period valley at lower companion mass** In their samples of radial velocity detected planets, Jones et al. (2003) and Udry et al. (2003c) noted a significant *period valley* (viz., a lack of planets) in the interval  $P = 10 - 100$  d. Udry et al. (2003c) showed that this is attributable to a lack of massive planets ( $M_p \sin i > 2 M_J$ ). These results were further confirmed, at least

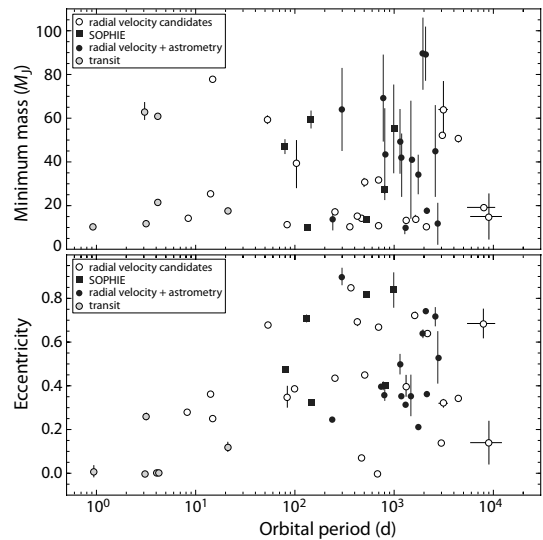


Figure 2.36: Radial velocity discoveries with (minimum) masses between  $9 - 90 M_J$  that orbit solar-type stars with  $P < 10^4$  d, showing the mass–period (top) and eccentricity–period relations. Objects classified through SOPHIE by Díaz et al. (2012) are shown as solid squares. Other symbols indicate companions for which the true mass is known from astrometry (black circles) or transits (grey circles). Open circles are radial velocity discoveries with no other mass information, with indicated mass interpreted as a ( $\sin i$  dependent) lower limit. From Díaz et al. (2012, Figure 13), reproduced with permission © ESO.

for more massive planets ( $M_p > 100 M_{\oplus}$ ), from four years of data on 24 bright stable stars from the Anglo–Australian Planet Search (Wittenmyer et al., 2010), which allowed rigorous detection limits to be placed on planetary companions in the range  $P = 2 - 300$  d. A possibly related paucity of close-in low-mass planets is seen in transiting planet samples, referred to as the ‘sub-Jovian desert’ (§6.27).

**Constraints on formation models** The brown dwarf desert has no unambiguous origin. It has been attributed to inward migration within an evolving protoplanetary disk (Armitage & Bonnell, 2002), or as signifying a different formation mechanism for the two (planetary and brown dwarf) populations (Matzner & Levin, 2005). It may emerge as a natural consequence of formation by core accretion, in which unimpeded dynamical accretion of gas is a runaway process that is terminated only when the residual gas is depleted either globally or locally in the form of a gap in the vicinity of their orbits. Since planet masses grow rapidly from 10 to  $100 M_{\oplus}$ , gas giants rarely form with asymptotic masses in this intermediate range. The model of Ida & Lin (2004a), for example, specifically predicts few objects in the range  $10 - 100 M_{\oplus}$  and  $a < 3$  au. The mass distribution in the desert region described by current population synthesis models is described further in Section 10.13.3.

Duchêne & Kraus (2013) suggested that tidal interaction with host stars may further shape the brown dwarf desert. Damiani & Díaz (2016) found that F-type stars may host massive companions for a significantly longer time than G-type stars for  $P < 5$  d; however, they conclude that brown dwarf occurrence rates should be largely unaffected by tidal decay for  $P \geq 10$  d, independent of host star mass.

Ma & Ge (2014) found that brown dwarf companions  $\lesssim 40M_J$  have an eccentricity distribution consistent with that of massive planets, while those of larger mass have an eccentricity distribution consistent with that of binaries. They also found that host stars of brown dwarf companions are not metal rich, and have a significantly different metallicity distribution compared to host stars of giant planets. They concluded that brown dwarfs  $\lesssim 40M_J$  likely form in a protoplanetary disk through gravitational disk instability, and their eccentricity is excited through scattering, while those of higher mass likely form in the same way as stars, through molecular cloud fragmentation (§9.7). Troup et al. (2016) found 14 brown dwarf candidates around metal-poor stars ( $[\text{Fe}/\text{H}] < -0.5$ ), perhaps consistent with the finding that lower metallicity populations generally have a higher number of binaries (Carney et al., 2003).

## 2.11 Results according to planet type

Based on 8 yr of HARPS data, Mayor et al. (2011) already found that more than 50% of solar-type stars harbour at least one planet of any mass and with  $P \lesssim 100$  d. The occurrence rate of gaseous giant planets grows with  $\log P$ , strongly increasing with host star metallicity, and with eccentricities up to 0.9 or more. Some 14% of solar-type stars have a planetary companion more massive than  $50M_{\oplus}$  with  $P < 10$  yr.

### 2.11.1 Low-mass planets

Udry & Mayor (2008) had already noted that, below  $\sim 0.1M_J$ , and despite the progressively smaller radial velocity variations and observational incompleteness, which together rendered the detection of lower mass planets more difficult, the frequency of low-mass planets was observed to rise. As of late 2010, eight planets were known with  $M \sin i < 0.02M_J$ , of which two were transit discoveries (CoRoT-7 b and GJ 1214 b).

By the end of 2017, some 45 radial velocity discoveries had  $M \sin i < 0.02M_J$  ( $\sim 6M_{\oplus}$ ) and some 20 below  $0.01M_J$  ( $\sim 3M_{\oplus}$ ), mostly in multiple systems with previously-detected planets.

Amongst the early low-mass discoveries were the  $7.5M_{\oplus}$  GJ 876 d in the 4-planet system (Rivera et al., 2005), the Neptune-mass 3-planet system around HD 69830 (Lovis et al., 2006; Ji et al., 2007), the 3-planet super-Earth system HD 40307 (Mayor et al., 2009b), and the 2-planet HD 215497 (Lo Curto et al., 2010).

The lowest mass planets are being discovered around the lowest mass stars. The three lowest mass discoveries, at  $0.002 - 0.003M_J$  ( $0.6 - 0.9M_{\oplus}$ ,  $P_{\text{orb}} = 2 - 5$  d) orbit the  $0.13M_{\odot}$  ( $d = 3.6$  pc) M dwarf YZ Cet (Astudillo-Defru et al., 2017b).

Low-mass planets are frequently found as members of multi-planet systems, and may indeed be found preferentially in multiple systems (Lo Curto et al., 2010).

Wittenmyer et al. (2011b) presented an analysis of 67 solar-type stars from the Anglo-Australian Planet

Search specifically targeted for high-precision observations. They found that planet occurrence increases strongly with decreasing planet mass. Their results are consistent with those from other surveys: for periods shorter than 50 d, they found that 3% of stars host a giant planet ( $M \sin i > 100M_{\oplus}$ ), and that 17% of stars host a planet with  $M \sin i < 10M_{\oplus}$ .

The discovery of so many low-mass planets, close to the detection threshold and over a relatively short period of the high-precision Doppler surveys, suggests the existence of a large population of low-mass planets, perhaps reaching 30% for G and K dwarfs (Mayor et al., 2009b). Some of the scatter in radial velocity measurements for individual objects is also likely to be attributable to undetected, low-amplitude, multi-planet systems.

**Eta Earth** The subject is covered in Chapter 6.

### 2.11.2 Super-Earths and Neptunes

Based on 8 yr of HARPS data, Mayor et al. (2011) found that the mass distribution for planets with  $M_p \lesssim 30M_{\oplus}$  (i.e. super-Earths and Neptunes) behaves differently from gaseous giant planets, increasing strongly between 30 and  $15M_{\oplus}$ , with  $e \lesssim 0.45$ , no preference for metal rich stars, and most belonging to multi-planetary systems.

Wolfgang & Laughlin (2012) reported that 30–50% of G and K dwarfs in the solar neighbourhood host planets with  $M_p < M_{\text{Neptune}}$  ( $17M_{\oplus}$ ) in orbits of  $P \lesssim 50$  d. To reconcile these numbers with the early (Q0–Q2) findings of the Kepler mission, that some 15% of main-sequence dwarfs harbour a short-period planet with  $R < 4R_{\oplus}$ , they hypothesised either a mass–density relationship extrapolated from the solar system, a population consisting of both dense silicate-iron planets and low-density gaseous planets, or a multi-valued mass–radius relationship, which allows planets of similar mass to have significantly different radii. In such a scenario, HARPS would be detecting a large population of dense low-mass planets, while Kepler detects a large population of gaseous sub-Neptunes.

### 2.11.3 High-mass planets

For the 1200 FGKM dwarfs in the solar neighbourhood monitored by the California and Carnegie Planet Search programme (Wright et al., 2004a), Marcy et al. (2008) report that 87% of stars observed for more than a decade show no Doppler variations at a  $3\sigma$  limit of  $10 \text{ m s}^{-1}$ . These limits largely exclude the existence of a significant number of undiscovered Jupiter-mass planets within 3 au, and Saturn-mass planets within 1 au.

At least 6–7% have giant planets, with  $M_p > 0.5M_J$  and  $a < 5$  au, a similar fraction also being reported by the Geneva group (Udry & Mayor, 2008). Some 15% of these fall into the category of ‘hot Jupiters’, with  $P \lesssim 10$  d, and orbiting very close to their host stars.

The remaining 6% of stars show long-term radial velocity trends, often with significant curvature, indicating substellar, brown dwarf, or planetary companions with orbital periods of a decade or more (Patel et al., 2007).

#### 2.11.4 Hot Jupiters

Wright et al. (2012) determined a fraction  $1.2 \pm 0.38\%$  of solar-type stars (FGK dwarfs) in the solar neighbourhood hosting hot Jupiters as measured by the California Planet Survey from the Lick and Keck planet searches. This is consistent with the fraction of  $0.89 \pm 0.36\%$  with  $M \sin i > 50 M_{\oplus}$  and  $P < 11$  d reported from HARPS and CORALIE (Mayor et al., 2011). These numbers are more than double those reported by Howard et al. (2012b) for Kepler stars, and the rate of Gould et al. (2006a) from the OGLE-III transit search, although of only marginal statistical significance due to the small sample size.

Further details on hot Jupiters are given elsewhere, including their overall occurrence rates in radial velocity and transit surveys summarised (§1.6.2), discovery and associated properties from transit observations (§6.28), and current understanding of their formation (§10.7.1).

## 2.12 Multi-planet systems

A number of general dynamical considerations relevant for multi-planet systems, which apply equally to systems found from transit experiments (notably Kepler), are considered in Chapter 10: including a description of resonances (§10.8), stability (§10.9), and chaotic orbits (§10.9.4).

### 2.12.1 General considerations

**Frequency of multiple systems** The first radial velocity target known to comprise multiple planets was the triple planetary system  $\nu$  And (Butler et al., 1999). This was followed by the discovery of a second planet orbiting 47 UMa (Fischer et al., 2002b), and a resonant pair orbiting GJ 876 (Marcy et al., 2001a). The tenth triple system, HIP 14810, was announced by Wright et al. (2009a).

Some 10–15% of systems discovered from radial velocity measurements are known to be multiple (Figure 2.38), with a further comparable fraction showing evidence for multiplicity in the form of long-term radial velocity trends. An increasing number continue to be discovered, partly as a result of improved accuracies, and partly as a result of longer measurement baselines.

Highest confirmed multiplicities are the 6-planet systems HD 10180, HD 34445, and HD 219134, and the 5-planet systems 55 Cnc, GJ 667C, and HD 40307. There are seven 4-planet systems.

Longer temporal coverage of known systems is leading to the discovery of outer companions with long orbital periods. More than 30 radial velocity discoveries

have  $P \gtrsim 10$  yr, with a few of 20–30 yr. Improved accuracy is leading to the discovery of numerous low-mass planets in multiple systems, with around 40 now known below  $0.02 M_J$  ( $6 M_{\oplus}$ ), and 20 below  $0.01 M_J$  ( $3 M_{\oplus}$ ).

**Co-planarity** The  $\sin i$  uncertainty for each planet means that the extent to which multiple systems have co-planar orbits is not well constrained by present observations. Numerical simulations, such as those by Thommes & Lissauer (2003), Adams & Laughlin (2003), and others, suggest that a significant fraction of planetary systems involving giant planets may be substantially non-coplanar. Dynamical mechanisms that lead to fast amplification of the relative inclination are especially effective in the first-order resonance configurations (Thommes & Lissauer, 2003). Also, dynamical relaxation and collisional scattering of protoplanets may favour large relative inclinations, even if they initially emerge in a flat protoplanetary disk.

Constraints on the relative orbital inclinations of individual systems are frequently presented on the basis of long-term numerical orbit integrations, which may reveal islands of stability or instability for certain hypothesised relative inclinations. Direct observations, from astrometric measurements, are restricted to systems with large astrometric signatures for each individual planet (§3.1). The 3-planet system  $\nu$  And, observed with HST-FGS, currently provides the most convincing example (§3.7), with the large relative inclination between planets c and d ( $\Delta i_{cd} = 29^{\circ}9 \pm 1^{\circ}$ ) lending preliminary support to the simulation results.

**Statistics of multi-planet systems** A difference between single and multiple planetary systems noted early on in the discovery of radial velocity planets is that the pile-up of hot Jupiters between 0.03–0.07 au, and the discontinuity at  $\sim 1$  au observed in the distribution of single systems, are both absent from the more uniform distribution seen in multi-planet systems (Figure 2.37). Systems with multiple giant planets appear to lead to a suppressed occurrence of close-in planets. Both characteristics presumably reflect details of migration in the two types of system. Various other differences in the properties of single and multiple systems, in  $M_p \sin i$ ,  $e$ , and  $M_*$ , the implications for migration models, and the possibilities of selection effects in the present samples, are considered further by Wright et al. (2009b).

**Dynamical modeling** In the basic kinematic (or ‘Keplerian’) fitting approach (§2.1.2), the total radial velocity signal due to  $n_p$  planets is assumed to result from the independent reflex motions due to each planet separately.

Many multi-planet systems may, however, show effects of gravitational planet–planet interactions, even over relatively short time scales. These can lead to observable evolution of the orbital parameters over periods of years, and to radial velocity variations of the star

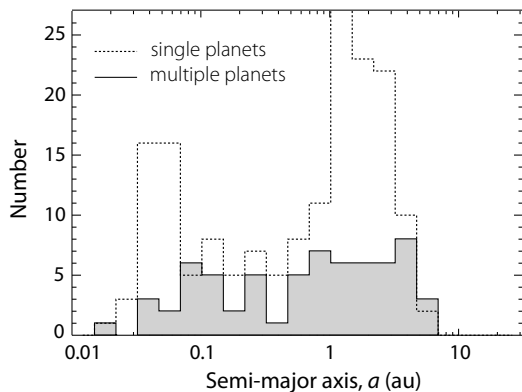


Figure 2.37: Distribution of semi-major axes for multiple planet systems (solid) and apparently single systems (dashed). The pile-up of hot Jupiters, and the jump in abundance beyond 1 au seen in the single planet systems are not evident in the multiple planet systems. From Wright et al. (2009b, Figure 9), by permission of IOP Publishing/AAS.

that differ substantially from those derived assuming the planets are executing independent Keplerian motions.

Dynamical analyses of these more complex systems are made using either of two approaches. N-body numerical integration methods are used both for dynamical (or ‘Newtonian’) orbit fitting (see also §2.1.2), and for studying the detailed planetary motions over relatively short time intervals in the future, including testing the validity of analytical results. N-body integration rests on the basic laws of gravity and motion. Results may yield ‘deprojected’ planetary masses (without the  $\sin i$  ambiguity) and, in favourable cases based on stability arguments, relative orbital inclinations.

Analytical methods make use of the *disturbing function*, the difference in gravitational potential due to a star alone, and that due to a star and other perturbing planets. Analytical theory successfully describes two principal phenomena seen in multiple systems: secular (non-periodic) evolution, and resonances.

In *secular theory*, terms that depend on the planet’s mean motion,  $n$ , as well as other higher-order orbit terms, are ignored, and the theory describes the system’s *secular evolution*, essentially predicting how the shape of an average orbit evolves with time. In most two planet systems, secular theory predicts that their eccentricities oscillate, with an increasing eccentricity of one planet (corresponding to an increase of orbital angular momentum) being accompanied by decreasing eccentricity of the other through conservation of angular momentum. Secular theory also predicts the general behaviour of the difference in the two longitudes of pericentre,  $\Delta\tilde{\omega}$ : depending on initial conditions,  $\Delta\tilde{\omega}$  may oscillate around 0 (aligned libration),  $2\pi$  (anti-aligned libration), or circulate through  $2\pi$ .

In *resonant theory*, terms that depend on the mean

motions are included, but only those related to the resonance under study are considered.

**Radial velocity systems in resonance** A number of multi-planet systems discovered by radial measurements (as well as many discovered through transit measurements) are found to be in orbital resonances (§10.8). Examples, and inferences that can be made from them, are considered in §2.12.4. From the complexity of the phenomenon it is apparent that very diverse systems, and complex behaviour in the long-term orbit integrations, can be expected. Table 2.7 list the apparent period commensurabilities for well-characterised radial velocity detected multi-planetary systems.

**Multiple systems and theories of formation** As developed in detail in Chapter 10, the core accretion model provides a compelling scenario for giant planet formation. In brief, from an embryonic disk of dust and gas, dust particles collide and grow to form progressively larger planetary cores. If a significant amount of gas remains in the disk, a sufficiently massive core can gravitationally accrete more gas, rapidly growing in mass. Such giant planets are likely to form beyond the snow line, at around 3 au for solar-type stars, where ices can participate in the initial planetary cores. The fact that some 20% of known exoplanets orbit within 0.1 au, where little ice is available, leads to the hypothesis that short-period planets formed far out and migrated inwards to their present locations.

The discovery of numerous systems in or near mean motion resonance lends support to migration, with hydrodynamical and N-body simulations with externally applied damping suggesting that the 2:1 mean motion resonance (and others) appear naturally as the planets migrate inwards at different rates. Various mechanisms may be responsible for the wide distribution of observed eccentricities, some driving eccentricities to larger values while damping others to low values. An early era of strong planet–planet scattering producing large values may be followed by a damping phase as a result of subsequent interactions with remaining planetesimals. Evidence for these various mechanisms are detailed in §2.12.3 and §2.12.4.

## 2.12.2 Architectures and classification

The multi-planet systems discovered from radial velocity measurements span a range of architectures. Wright (2010) classified them into five broad and non-exclusive categories: systems with three or more giants (§2.12.3), systems with two giants in mean motion resonance (§2.12.4), other systems in which planet–planet interactions are non-negligible (§2.12.5), non-interacting systems (§2.12.6), and systems containing only lower mass planets with  $M_p \sin i < 20M_\oplus$  (§2.12.7).

This somewhat arbitrary classification nevertheless serves as a guide for the following discussions of various dynamical effects observed in multi-planet systems.

## 2.12.3 Systems with three or more giant planets

A few multiple radial velocity systems are considered here in some detail, in order to illustrate the kind of analysis and insight that is possible for these systems. A number of other such systems are now known.



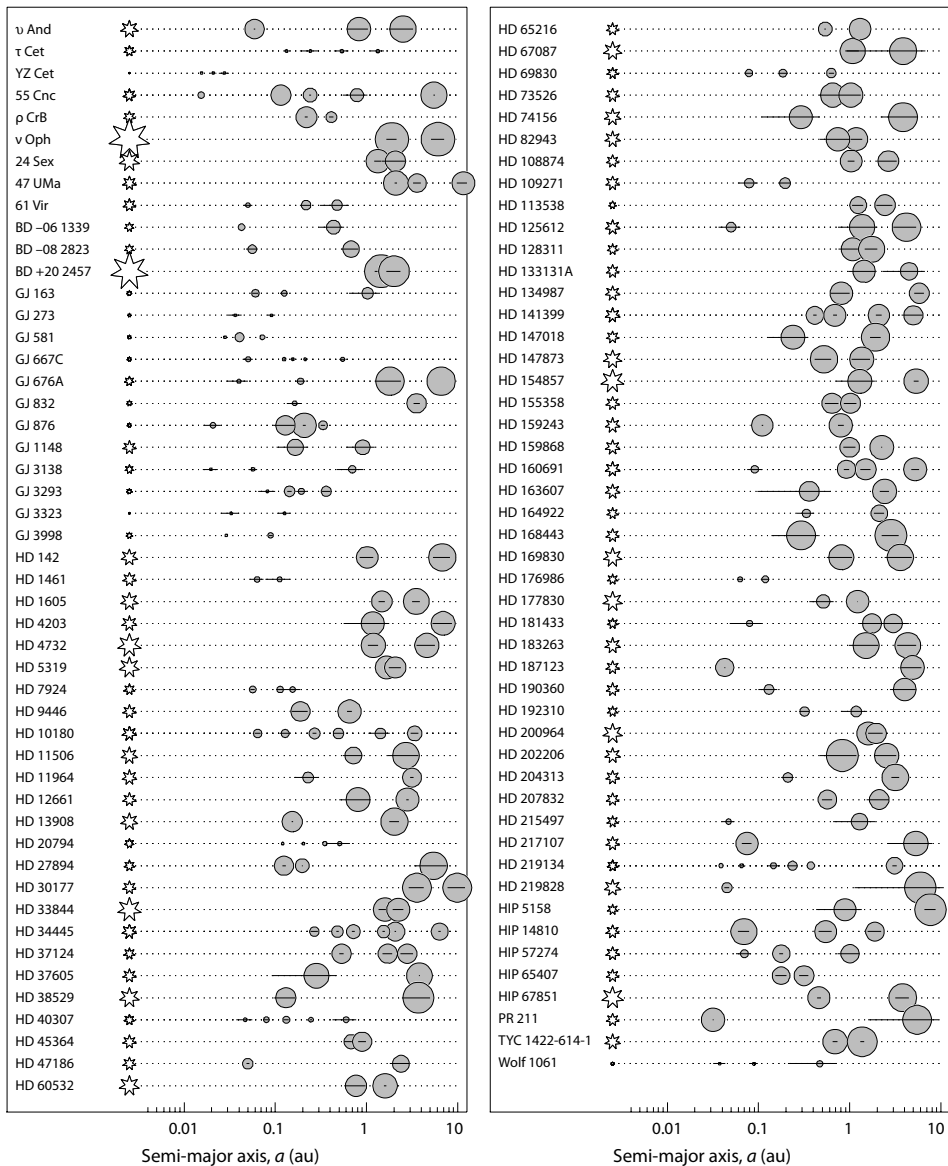


Figure 2.38: Radial velocity discovered systems of multiplicity 2 or higher, from the NASA Exoplanet Archive, 2017 December 31 (245 planets in 97  $n \geq 2$  systems). The host star mass is represented at left with size proportional to  $M_\star$  (ranging from  $0.13M_\odot$  for YZ Cet to  $3.0M_\odot$  for  $\nu$  Oph). Each planet in the system is shown to the right, with size  $\propto \log M_p$  (from  $0.002M_J$  for YZ Cet b to  $27M_J$  for  $\nu$  Oph c). Solid horizontal lines indicate maximum and minimum star–planet distance from their eccentricities. Highest multiplicities (6) are for HD 10180, HD 34445, and HD 219134. A similar plot for transiting systems is given in Figure 6.114.

**$\nu$  And** The first system discovered to be multiple was the 3-planet system  $\nu$  And. In addition to the  $0.6 M_J$  object in a low-eccentricity 4.6-d orbit originally detected by Butler et al. (1997), two more distant planets were identified from subsequent radial velocity observations, with  $M_p \sin i$  of 2.0 and  $4.1 M_J$ ,  $a$  of 0.82 and 2.5 au, and large  $e$  of 0.23 and 0.36 respectively (Butler et al., 1999). Evidence of a fourth outer planet from the Keplerian fits ( $M_p \sin i = 1.06M_J$ ) was reported by Curiel et al. (2011).

Various work has addressed its stability (Holman et al., 1997; Krymowski & Mazeh, 1999; Laughlin & Adams, 1999; Lissauer, 1999; Rivera & Lissauer, 2000; Stepinski et al., 2000; Barnes & Quinn, 2001; Chiang et al., 2001; Jiang & Ip, 2001; Lissauer & Rivera, 2001; Chiang & Murray, 2002; Michtchenko & Malhotra, 2004; Michtchenko et al., 2006; Libert & Henrard, 2007; Rivera & Haghighipour, 2007; Libert & Tsiganis, 2009a; McArthur et al., 2010; Libert & Sansottera, 2013; Deitrick et al., 2015).

Table 2.7: Apparent period commensurabilities for well-characterised radial velocity detected multi-planetary systems (similar commensurabilities occur for transiting systems), based on Wright et al. (2011c, Table 3).

System	Planets	Period ratio	Reference
$\mu$ Ara	b, e	2:1	Pepe et al. (2007); Goździewski et al. (2007)
24 Sex	c, b	2:1	Johnson et al. (2011b); Wittenmyer et al. (2012b)
GJ 876	e, c, b	4:2:1	Marcy et al. (1998); Rivera & Lissauer (2001)
55 Cnc	c, b	3:1	Fischer et al. (2008); Zhou et al. (2008)
HD 10180	d, e	3:1	Lovis et al. (2011)
HD 10180	e, f	5:2	Lovis et al. (2011); Tuomi (2012)
HD 37124	c, d	2:1	Vogt et al. (2005); Wright et al. (2011c)
HD 45364	c, b	3:2	Correia et al. (2009); Rein et al. (2010); Correa-Otto et al. (2013)
HD 60532	c, b	3:1	Desort et al. (2008); Laskar & Correia (2009); Desort et al. (2009a); Alves et al. (2016)
HD 73526	c, b	2:1	Tinney et al. (2006); Sándor et al. (2007a); Zhang et al. (2010); Wittenmyer et al. (2014b)
HD 82943	b, c	2:1	Ji et al. (2003a); Mayor et al. (2004); Lee et al. (2006); Baluev & Beaugé (2014)
HD 108874	c, b	4:1	Vogt et al. (2005); Goździewski et al. (2006)
HD 128311	c, b	2:1	Vogt et al. (2005); Sándor & Kley (2006); Zhang et al. (2010)
HD 200964	c, b	4:3	Johnson et al. (2011b); Wittenmyer et al. (2012b); Tadeu dos Santos et al. (2015)
HD 202206	c, b	5:1	Correia et al. (2005); Goździewski et al. (2006)

**Dynamical insights** The innermost planet, with  $e \sim 0$ , significantly exceeds the minimum stability requirement given by the Hill radius criterion, suggesting little interaction with the outer two companions. For the two planets c and d in contrast, the system stability depends strongly on the planet masses, and hence their relative orbital inclinations, with certain combinations implying chaotic or unstable orbits.

Mazeh et al. (1999) derived a mass for planet d of  $10.1 \pm 4.7 M_J$  using Hipparcos astrometry, implying  $i = 156^\circ$ , and masses of the inner two planets of  $1.8 \pm 0.8$  and  $4.9 \pm 2.3 M_J$  if the orbits are co-planar (see also Reffert & Quirrenbach 2011). Astrometry from HST has established the mutual inclination of planets c and d as  $\sim 30^\circ$  (discussed further in §3.7).

Goździewski et al. (2001) used the fast orbit indicator MEGNO to derive  $\langle \mathcal{I} \rangle(t)$  as a function of the inclination of planet c, and the relative inclination of planets c and d (Equation 3.17). Quasi-periodic and chaotic zones are evident in various regions of the  $i_c, i_{c-d}$  parameter space (Figure 10.32).

From numerical integration using Mercury, Ford et al. (2005) found that for a co-planar configuration the system becomes dynamically unstable when  $\sin i < 0.5$  while, if the coplanarity condition is relaxed, dynamical instability resulted from relative inclinations  $\geq 40^\circ$ . They found that the long-term secular evolution of the orbits (Figure 10.33) was best modeled as resulting from an impulsive perturbation to planet d, in which a sudden change in its eccentricity was produced by a close encounter with another planet. After a brief period of chaotic evolution lasting  $\sim 10^3$  yr, the perturbing planet would have been ejected, leaving the remaining planets (c and d) in a stable configuration resembling that observed today.

With the discovery of the fourth planet,  $\nu$  And e, numerical integration of the orbital solution for all four planets (Curiel et al., 2011) showed that the system is stable for at least 10 Myr, with the orbit of the fourth planet coinciding with an island of stability reported by Rivera & Haghighipour (2007). All four planets have very strong mutual interactions, with planets b and c in apsidal alignment, and the orbit of planet e being close to an external 3:1 resonance with planet c.

With no observational constraints on the orbital plane of planet b, Deitrick et al. (2015) used N-body simulations to search for stable three-planet configurations that are consistent with the combined radial velocity and astrometric solu-

tion, finding that the orbit of planet b must lie near the invariable plane of planets c and d, but can be either prograde or retrograde. Their solutions predict that the mass of planet b is in the range  $2 - 9 M_J$ , with an inclination angle from the sky plane of  $< 25^\circ$ . Combined with brightness variations in the combined star/planet light curve (or phase curve) determined by Harrington et al. (2006) and Crossfield et al. (2010), their results imply that  $R_b = 1.8 R_J$ , relatively large for a planet of its age. But with  $e_b > 0.1$  in several of their stable solutions, generating upward of  $10^{19}$  W in the interior of the planet via tidal dissipation (as also inferred for HD 209458 b by Ibgui & Burrows 2009), the radius could be inflated by an amount consistent with the phase curve observations.

**HD 37124** HD 37124 is an example of dynamical stability modeling leading to the discovery of additional planets. Vogt et al. (2000) detected a 150-d Jupiter-mass planet from Keck-HIRES observations. Butler et al. (2003) identified a second planet with  $P \sim 6$ -yr. The two-planet solution was shown to be unstable by Goździewski (2003a), with further Keck data identifying a third planet (Vogt et al., 2005).  $\{M_p \sin i (M_J), P (d), e\}$  for planets b, c, d are respectively  $\{0.638, 154, 0.055\}$ ,  $\{0.697, 2300, 0.2\}$ ,  $\{0.624, 844, 0.14\}$ . Further dynamical studies have been undertaken (Goździewski et al., 2006, 2008a; Wright et al., 2011c; Elser et al., 2013).

**HD 74156** The two planet system was originally reported by Naef et al. (2004) from ELODIE data. A third planet was detected from a combination of CORALIE, ELODIE and HET-HRS data by Bean et al. (2008b), with  $M_p \sin i = 0.40 M_J$ ,  $P = 347$  d, and  $e = 0.25 \pm 0.11$ .

**Predicting planet d** Raymond & Barnes (2005) had predicted the parameter space that such a third planet could have occupied (also in three other systems), by identifying stability regions for massless test particles defined by the previously known planets. For HD 74156 they had shown that a Saturn mass planet could exist within a broad region of  $a = 0.9 - 1.4$  au and  $e \leq 0.15$ . Barnes et al. (2008b) gave an alternative slightly improved orbit, and suggested that the confirmed prediction of

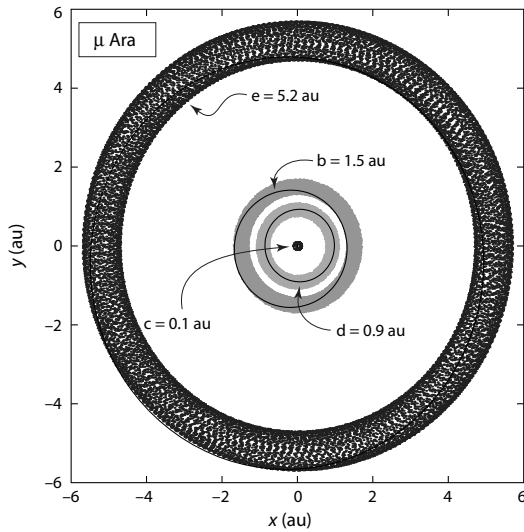


Figure 2.39: Face-on view of  $\mu$  Ara (HD 160691), illustrating orbital evolution of the four planets over 1 Myr. Present orbits are shown as solid lines, while dots (indistinguishable here for the inner three planets) correspond to positions every 50 yr. The values of  $a$  are constant, while the eccentricities undergo small variations in the range 0.09–0.13, 0.16–0.21, 0–0.19, and 0.08–0.11 for planets b–e respectively. From Pepe et al. (2007, Figure 6), reproduced with permission © ESO.

the third planet points to planet formation being an efficient process, with systems typically containing many planets.

**$\mu$  Ara (HD 160691)** The properties of this four-planet system were progressively revealed by AAT–UCLES (Butler et al., 2001; McCarthy et al., 2004) and HARPS (Santos et al., 2004a; Pepe et al., 2007) data. The fourth planet was also tentatively announced by Goździewski et al. (2007). Simulations demonstrating the system stability are shown in Figure 2.39. The semi-major axes remain almost constant, while the eccentricities of all four planets undergo small variations. Various other dynamical analyses have also been made (Bois et al., 2003; Goździewski et al., 2003, 2005a; Short et al., 2008).

**55 Cnc** The 55 Cnc system was the first known planetary system comprising five planets (Table 2.8). The first, 55 Cnc b, was reported by Butler et al. (1997), and the second (and possibly a third) also from Lick data by Marcy et al. (2002). 55 Cnc c was confirmed by McArthur et al. (2004) based on Lick, ELODIE and HET Doppler measurements and HST–FGS astrometry. They also announced 55 Cnc e with  $P = 2.8$ -d.

**Dynamical insights** Fischer et al. (2008) used 18 years of Lick and Keck data to confirm the four proposed planets, and to identify a fifth, 55 Cnc f, moving in the large empty zone between two other planets. All five reside in low-eccentricity orbits, four having  $e < 0.1$ . They adopted a multi-planet Keplerian fitting procedure (§2.1.2), using a numerical N-body simulation to show that the system is dynamically stable.

Table 2.8: The planets of 55 Cnc, ordered by increasing semi-major axis. Data are from Fischer et al. (2008), and do not include possible updates suggested by Nelson et al. (2014b).

Planet	$M_p \sin i$ ( $M_J$ )	$a$ (au)	$P$ (d)	$e$
e	0.02	0.038	2.80	0.26
b	0.83	0.115	14.65	0.02
c	0.17	0.240	44.38	0.05
f	0.15	0.789	260.67	0.00
d	3.90	5.888	5371.82	0.06

55 Cnc has some basic structural attributes found in our solar system: the orbits are rather circular and nearly co-planar, and a dominant gas giant lies at a distance of about 6 au. Although planets b and c have a period ratio of 3.027:1.000, hinting at a possible mean motion resonance (Marcy et al., 2002; Ji et al., 2003b; Voyatzis & Hadjidemetriou, 2006), the 3:1 mean motion resonance was excluded by the N-body model of Fischer et al. (2008), as later confirmed by Nelson et al. (2014b), as none of the relevant resonant arguments librate.

Other dynamical simulations were made by Gayon et al. (2008) using MEGNO, who found that about 15% of the systems resulting from the nominal orbital elements of the system are highly chaotic. Raymond et al. (2008b) evaluated the stability of the large region between planets f and d using N-body integrations that included an additional, yet-to-be-discovered planet g with a radial velocity amplitude of  $\sim 5 \text{ m s}^{-1}$ , i.e.  $M_p \approx 0.5 - 1.2 M_{\text{Saturn}}$ . They found a large stable zone extending from 0.9–3.8 au with  $e < 0.4$ , which could contain 2–3 additional planets each of  $M_p \sim 50 M_{\oplus}$ . Any planets exterior to planet d must reside beyond 10 au.

N-body simulations using 1418 high-precision radial velocity observations from four observatories (Lick, Keck, HET, and HJS), along with transit times (and durations) for the innermost planet, 55 Cnc e, was made by Nelson et al. (2014b). Amongst their findings were that dynamical stability dictates that the orbital plane of planet e must be aligned to within  $60^\circ$  of the orbital plane of the outer planets, assumed to be co-planar.

#### 2.12.4 Systems in mean motion resonance

**The 2:1 resonance system GJ 876** GJ 876 was the first known M-dwarf host. The orbit elements are particularly well determined due to their short periods, and orbit modeling shows that the two most massive planets b and c are locked in a 2:1 resonance, the first to be discovered amongst exoplanet systems.

**2:1 mean motion resonance** Marcy et al. (1998) using Keck, and Delfosse et al. (1998) using ELODIE/CORALIE, both reported a 61-d,  $2 M_J$  planet. From further Keck observations, Marcy et al. (2001a) showed that the radial velocity signal was actually the combination of two planets in a 2:1 mean motion resonance, with the inner having  $P = 30.1$  d and  $0.6 M_J$ . In the original data, the inner companion was indistinguishable from an additional orbital eccentricity of the outer. The axes of the two orbits are nearly aligned, and the orbital elements evolve significantly with time. A third, non-interacting,  $7.5 M_{\oplus}$  mass planet in a 1.9 d orbit was detected by Rivera et al. (2005).

Laughlin & Chambers (2001), Rivera & Lissauer (2001), and Nauenberg (2002a) independently developed fitting procedures to account for the gravitational interactions between the

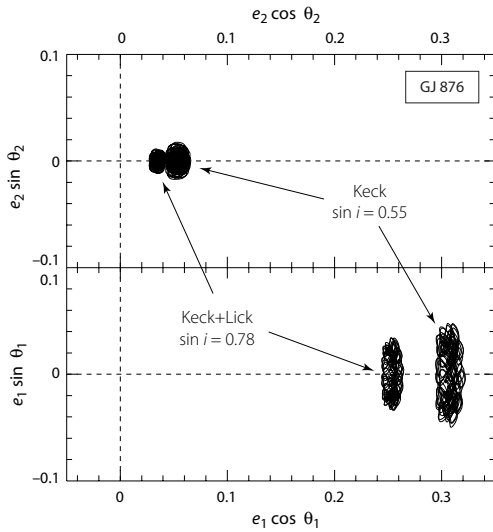


Figure 2.40: Small-amplitude librations, about  $0^\circ$ , of the two 2:1 mean motion resonance variables for GJ 876. Trajectories for 3100 d (the average pericentre precession period for both planets) are shown as  $e_j \sin j$  versus  $e_j \cos j$  ( $j = 1, 2$ ) for the best-fit solutions to the Keck data alone, and for the combined Keck and Lick data, both from Laughlin & Chambers (2001). Values of  $\sin i$  are obtained in the best-fit solution. From Lee & Peale (2002, Figure 1), by permission of IOP Publishing/AAS.

two outer planets. Rivera & Lissauer (2001) found that most of their solutions are stable for at least  $10^8$  yr, while test particles orbiting between the two planets are lost in  $\lesssim 300$  yr.

Lee & Peale (2002) showed that both mean motion resonance variables,  $\phi_1 = 2\lambda_2 - \lambda_1 - \bar{\omega}_1$  and  $\phi_2 = 2\lambda_2 - \lambda_1 - \bar{\omega}_2$  (cf. Equation 10.33), perform very small amplitude librations around  $0^\circ$  (Figure 2.40). Their simultaneous libration about  $0^\circ$  implies that the variable  $\phi_3 = \phi_1 - \phi_2 = \bar{\omega}_1 - \bar{\omega}_2$  also librates around  $0^\circ$ , and the planets are consequently in three resonances at the 2:1 mean motion commensurability. The small libration of  $\phi_3$  means that the lines of apsides of the two orbits are therefore nearly aligned, and conjunctions of the two planets occur very close to their longitudes of pericentre (Beaugé & Michtchenko, 2003).<sup>12</sup> The existence of the mean motion resonance is taken as confirmation that the two orbits are essentially co-planar, with the deep resonance (i.e. with small libration amplitudes) implying that the system is stable indefinitely.

Laughlin et al. (2005a) incorporated additional data obtained over 16 yr, and confirmed the small libration amplitudes (Figure 2.41). Such a configuration can be explained by a slow differential migration resulting from an interaction of the planets with a protoplanetary disk (Snellgrove et al., 2001; Lee & Peale, 2002; Kley et al., 2005; Beaugé et al., 2006; Crida et al., 2010b). They also showed that configurations with modest mutual inclinations are possible, which has an interesting corollary: for non-coplanar configurations the line of nodes of the inner planet precesses at about  $-4^\circ \text{ yr}^{-1}$ .

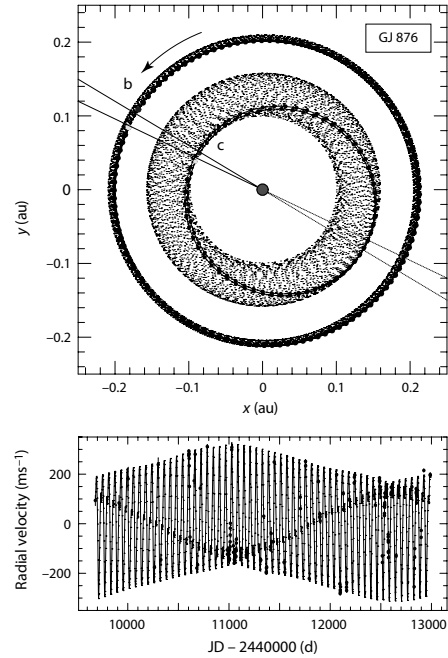


Figure 2.41: The 2:1 mean motion resonance in GJ 876. Top: the two clouds of dots show the planet positions every 0.5 d over 10 yr, illustrating precession in the line of apsides of  $-41^\circ \text{ yr}^{-1}$ . Connected circles show the planet positions every 0.5 d for 60 d. The two lines radiating from the central star mark the longitudes of pericentre,  $\bar{\omega}_b$  and  $\bar{\omega}_c$ , at JD 2449 710. They oscillate about alignment with a libration amplitude of  $34^\circ$ . Bottom: the stellar reflex velocities (circles), and the solution from the self-consistent, co-planar, 3-body integration. From Laughlin et al. (2005a, Figures 1–2), by permission of IOP Publishing/AAS.

The inner planet may therefore be observed to transit the host star at some time in the relatively near future, i.e. when either the ascending or descending node precesses through the line-of-sight, even though it is not transiting at the present time. This general phenomenon of ‘transitional transits’ is described further in Section 6.19.8.

**Laplace resonance** A fourth planet, GJ 876 e, was discovered from continued radial velocity monitoring by Rivera et al. (2010b). N-body fits show that the four-planet system has an invariable plane with an inclination of  $59^\circ.5$ , and is stable for more than 1 Gyr. Their model places the fourth planet in a three-body ‘Laplace’ resonance ( $\S 10.8.3$ ) with the two giant planets ( $P_c = 30.4 \text{ d}$ ,  $P_b = 61.1 \text{ d}$ ,  $P_a = 126.6 \text{ d}$ ). Unlike the case of the Galilean satellites of Jupiter (Figure 2.42), the three planets come close to a triple conjunction once per orbit of planet e. The critical argument for the Laplace resonance,  $\phi = \lambda_c - 3\lambda_b + 2\lambda_e$ , librates with an amplitude of  $40^\circ \pm 13^\circ$ .

**The 2:1 resonance system HD 128311** The two-planet system HD 128311 offers an interesting insight into planetary migration along similar lines. The first planet was reported by Butler et al. (2003), and the second by Vogt et al. (2005). A Trojan 1:1 solution was suggested by Goździewski & Konacki (2006), while the most recent orbit solution is given by Wittenmyer et al. (2009).

<sup>12</sup>The nature of the resonance contrasts with the case of the Io–Europa system, where the lines of apsides are anti-aligned, and where conjunctions therefore occur when Io is near its pericentre, and Europa is near its apocentre.

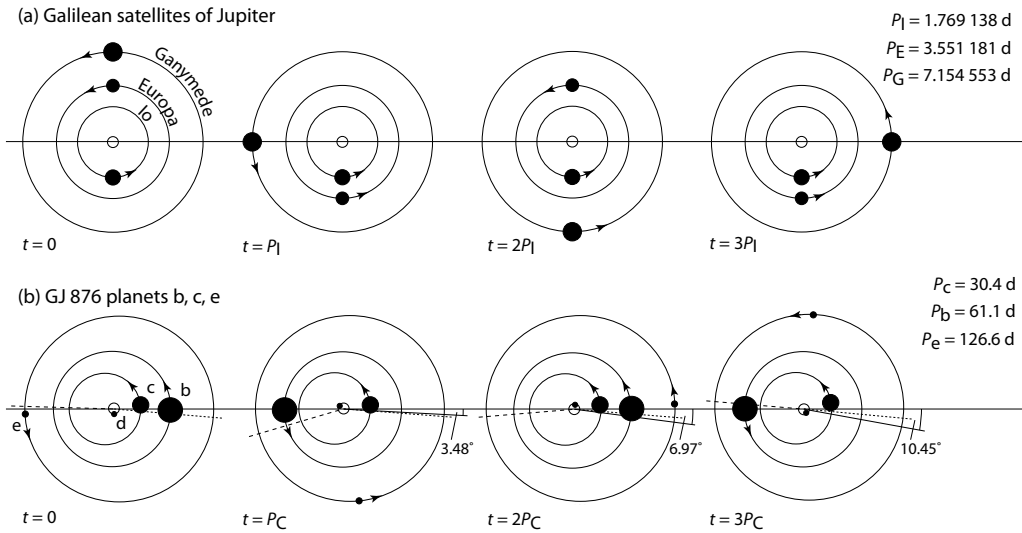


Figure 2.42: The first two known examples of Laplace resonance, in which three (or more) orbiting bodies have a simple integer ratio between their orbital periods: (a) Jupiter’s inner satellites Ganymede, Europa, and Io are in a 1:2:4 Laplace resonance, with Ganymede completing 1 orbit in the time that Europa makes 2, and Io makes 4. They never experience triple conjunctions. Their mean motions (Equation 2.8) are related by  $n_I - 3n_E + 2n_G = 0$ , satisfied to nine significant figures (Peale, 1976); (b) planets c, b, e of the M dwarf host star GJ 876 are an exoplanet triplet in a Laplace resonance. The reference frame rotates at the mean orbital precession of planet b,  $-10^\circ\ 45$  over 90 d (solid lines). The apsidal line of b coincides with the x-axis, while those for planets c and e are shown with short-dash and long-dash lines respectively. In each system, the orbits and object radii (assuming  $R \propto M^{1/3}$ ) are shown to scale. The lower figure is adapted from Rivera et al. (2010b, Figure 7).

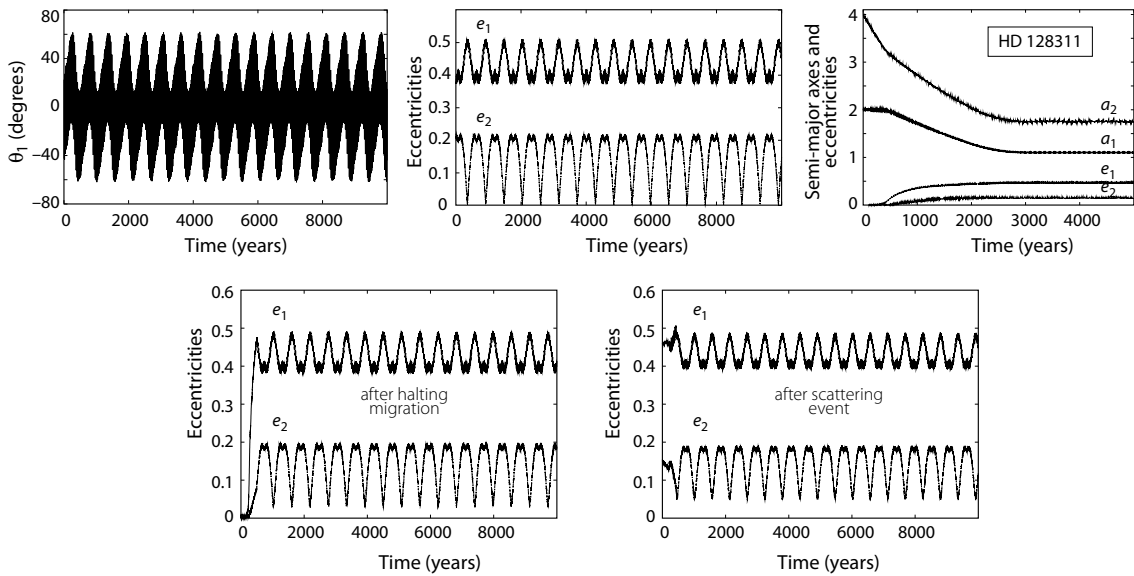


Figure 2.43: Resonant evolution of HD 128311. Evolution of the resonant angle  $\phi_1$  (top left) and eccentricities  $e_1$  and  $e_2$  (top middle) obtained by numerical integration of the orbital parameters of Vogt et al. (2005). Top right: predicted behaviour of the semi-major axes and eccentricities during adiabatic migration with an e-folding time of  $2 \times 10^3$  yr; for the simulations, the ongoing migration is progressively stopped between  $2 - 3 \times 10^3$  yr. Bottom left: evolution of the planetary eccentricities, both originally in circular orbits, following a sudden halting in the migration of the outer planet. Bottom right: evolution of the eccentricities following a scattering event with a low-mass planet migrating outwards. From Sándor & Kley (2006, Figures 1, 2, 3, 5), reproduced with permission © ESO.

**Solar system 1:1 resonances and the Trojans:** In the circular restricted three-body problem, three bodies move in circular co-planar orbits, with the mass of the third being negligible. In 1772, Lagrange proved the existence of five equilibrium points where the third particle has zero velocity and zero acceleration in the rotating frame. These are the three colinear Lagrangian equilibrium points  $L_1, L_2, L_3$ , and two (leading and trailing) triangular equilibrium points  $L_4, L_5$ . Although  $L_1-L_3$  are unstable, special starting conditions of the third particle, in position and velocity, can nevertheless result in semi-stable periodic orbits in their vicinity. This is exploited by artificial satellites such as SOHO which observes the Sun, interior to Earth's orbit, from  $L_1$  (Domingo et al., 1995), and deep-space missions which observe 'outward' from  $L_2$  (e.g., WMAP, Herschel, Planck, and Gaia).

Stable orbits in the vicinity of  $L_4$  or  $L_5$  were first demonstrated by Routh (1875) for the special case of circular orbits, and by Danby (1964a,b) for elliptical orbits. They comprise a short-term component of motion with a period close to the orbital period, and a longer term periodic motion about the equilibrium point referred to as libration. Resulting orbits can be described as a short-period epicyclic motion around a long-period motion of the epicentre, the relative contributions of the two components determined by the starting conditions. The resulting elongated orbits around  $L_4$  or  $L_5$  are referred to as *tadpole orbits*. For an increased radial separation from  $L_4$  or  $L_5$ , the resulting *horseshoe orbits* can encompass both  $L_4$  and  $L_5$ .

Examples of solar system bodies in such stable 1:1 resonances are referred to as *Trojans*, and they include both asteroids and satellites. Librating mostly in tadpole orbits around the Sun–Jupiter triangular equilibrium points is the leading group around  $L_4$  (the 'Greeks'), including the first known (588) Achilles discovered by Max Wolf in 1906, and the trailing group around  $L_5$  (the 'Trojans'). Typical libration amplitudes are  $15-20^\circ$  (Shoemaker et al., 1989).

Other Trojan asteroids orbit the Sun–Mars system, with the first (5261) Eureka, discovered in 1990, librating about  $L_5$  (Mikkola et al., 1994). Asteroid (3753) Cruithne is in a horseshoe orbit around the Sun–Earth system (Wiegert et al., 1997).

The dynamics of planet–satellite systems around their triangular equilibrium points are identical, and result in the *co-orbital* or *Trojan satellites*. Telessto and Calypso librate around the Saturn–Tethys system, and Helene and Polydeuces around Saturn–Dione. In the Janus–Epimetheus Saturnian system, Epimetheus moves in a horseshoe orbit, exchanging altitude with Janus as they approach in a 4 yr repeating cycle (Dermott & Murray, 1981a,b), and resulting in forced rotational libration (Tiscareno et al., 2009). Solitary density waves are launched when they exchange radial position (Rehnberg et al., 2016).

**Dynamical insights** Sándor & Kley (2006) performed a 3-body integration of the (Newtonian) orbital solution of Vogt et al. (2005), and examined the evolution of the difference in longitudes of pericentre  $\Delta\tilde{\omega} = \tilde{\omega}_2 - \tilde{\omega}_1$ , and the two appropriate resonant angles  $\phi_1, \phi_2$  (Equation 10.33 corresponding to  $\tilde{\omega}_1, \tilde{\omega}_2$  respectively). Of these, only  $\phi_1$  librates around  $0^\circ$  with an amplitude of  $\sim 60^\circ$ , while  $\phi_2$  and  $\Delta\tilde{\omega}$  rotate. At the same time, the eccentricities show large oscillations (Figure 2.43).

This behaviour contrasts with the apsidal corotation predicted by adiabatic migration (Figure 2.43, top right). Instead, Sándor & Kley (2006) considered that the system's state arises from a strong scattering event in the past. Assuming that the two planets were once locked in a 2:1 resonance with apsidal corotation as a result of inward migration, they then studied two distinct perturbation scenarios which might have disrupted the corotation (Figure 2.43, bottom). The first scenario invokes a sudden halting of migration. This might arise if the outer planet reaches some disk discontinuity with an empty region inside, possibly due to stellar photoevaporation (§10.3.6).

In the second scenario, an encounter with a low-mass  $10M_\oplus$  planet approaching from inside or outside (similar to that proposed by Ford et al. 2005 for  $\nu$  And) could also break the apsidal libration. The smaller planet would be ejected from the system, or perturbed into a larger orbit, in the process. Particularly in the case of a small planet approaching from the inside, the apsidal corotation of the giant planets is indeed broken. Consistent with the behaviour predicted from long-term orbit integration,  $\phi_2$  and  $\Delta\tilde{\omega}$  then circulate, while the giant planets remain in the 2:1 resonance, with  $\phi_1$  still librating around  $0^\circ$ .

**The 3:1 antisymmetric resonance system HD 60532** Amongst suggested systems in a 3:1 mean motion resonance are the two giants orbiting HD 60532 (Desort et al., 2008; Laskar & Correia, 2009; Sándor & Kley, 2010). The two orbital solutions found by (Laskar & Correia, 2009) have very different inclinations,  $i = 20^\circ$  or  $i = 90^\circ$ , with planet masses differing by a factor  $1/\sin i \sim 3$ .

**Dynamical insights** Sándor & Kley (2010) carried out detailed 2d hydrodynamical simulations of appropriate thin disks with an embedded pair of massive planets, studying the effects of migration and resonant capture using N-body simulations.

For resonant capture, planet pairs must undergo convergent migration, such that if the inner planet migrates inwards at the same speed, or faster than the outer one, then no resonant capture occurs. Resonant capture through migration therefore depends on the inner planet opening a suitably large gap in the inner disk to slow down its inward migration rate. In their simulations, Sándor & Kley (2010) found that capture into the observed 3:1 resonance takes place only for higher planetary masses, thus favouring orbital solutions having the smaller inclination of  $i = 20^\circ$  (Figure 2.44).

They also found that the inner disk, between the inner planet and the star, plays a key role in determining its final configuration. Specifically, fast inward migration of the outer planet may result in it crossing the 3:1 mean motion resonance without capture, ending the migration in the more robust 2:1 mean motion resonance. In the case of HD 60532, the damping effect of the disk on the inner planet's eccentricity is responsible for an antisymmetric (antialigned) resonance configuration in which  $\tilde{\omega}_2 - \tilde{\omega}_1$  oscillates around  $180^\circ$ , rather than the  $0^\circ$  in the case of aligned pericentres.

**Other mean motion resonances** Other systems believed to be in a 2:1 mean motion resonance include HD 82943 (Goździewski & Maciejewski, 2001; Ji et al., 2003a; Mayor et al., 2004; Ferraz-Mello et al., 2005; Lee et al., 2006); HD 73526 (Tinney et al., 2003b, 2006; Sándor et al., 2007a); and  $\mu$  Ara d–b (Pepe et al., 2007).

Other possible 3:1 resonances include 14 Her (Goździewski et al., 2006, 2008b), and the more contested case of 55 Cnc b–c (Marcy et al., 2002; Ji et al., 2003b; Fischer et al., 2008).

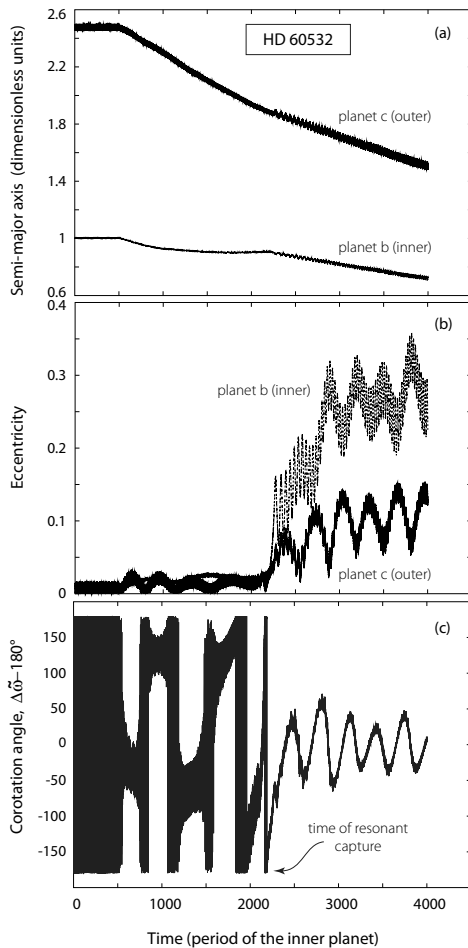


Figure 2.44: Dynamical simulation of the two giant planets orbiting HD 60532, embedded in a protoplanetary disk, showing (a) semi-major axes, (b) eccentricities, and (c) the evolution of the resonant angle  $\Delta\tilde{\omega} = \tilde{\omega}_2 - \tilde{\omega}_1$ . During the first 500 orbits of the inner planet, the planets are ‘fixed’ to obtain a steady state in the disk. Capture into the 3:1 mean motion resonance occurs after  $\sim 2300$  periods of the inner planet, subsequent to which the orbits exhibit (antialigned) apsidal corotation. The planetary masses ( $3.15M_J$  and  $7.46M_J$ ) correspond to a (co-planar) system inclination of  $i = 20^\circ$ . From Sándor & Kley (2010, Figures 4 and 5b), reproduced with permission © ESO.

A number of other possible resonances have been identified: the 4:1 resonance of HD 108874 (Butler et al., 2003; Goździewski et al., 2006) and perhaps 14 Her (Wittenmyer et al., 2007); the 5:1 resonance of HD 202206 (Udry et al., 2002; Correia et al., 2005; Goździewski et al., 2006); a possible 3:2 resonance of HD 45364 (Correia et al., 2009; Rein et al., 2010); a possible 5:2 resonance of HD 37124 (Goździewski et al., 2006); a possible 6:1 or 11:2 resonance of HD 12661 (Goździewski, 2003b; Lee & Peale, 2003; Rodríguez & Gallardo, 2005; Zhang & Zhou, 2006; Veras & Ford, 2009); and a possible 5:2 or 7:3 resonance in 47 UMa (Laughlin et al., 2002).

**Proximity to resonance** Proximity to a resonance may still affect the secular motion, as in the case of the near 5:2 resonance between Jupiter and Saturn, Laplace’s ‘great inequality’ (e.g. Varadi et al., 1999; Michtchenko & Ferraz-Mello, 2001a). Such proximity has been suggested for HD 12661 and  $\nu$  And (Libert & Henrard, 2007).

**Inclination resonance** In the absence of observational data on the mutual inclination of exoplanet orbits, most studies of mean motion resonances have focused on co-planar configurations. The extension to non-coplanar orbits is relevant for an understanding of eccentricity excitation and migration.

Thommes & Lissauer (2003) found that, subsequent to a 2:1 eccentric resonance capture, a subsequent capture into a 4:2 *inclination resonance* is possible. This is the lowest-order inclination resonance at the 2:1 commensurability (since the mutual inclination appears first as  $(\Delta i)^2$  in the series expansion of the disturbing function), and is characterised by the mean motion resonance variables (cf. Equation 10.36)

$$\begin{aligned}\phi_{11} &= 2\lambda_1 - 4\lambda_2 + 2\Omega_1 \quad \text{and} \\ \phi_{22} &= 2\lambda_1 - 4\lambda_2 + 2\Omega_2, \end{aligned} \quad (2.56)$$

where  $\Omega_j$  are the longitudes of the ascending nodes. The properties and subsequent evolution of this resonance are detailed by Lee & Thommes (2009).

Capture into higher-order resonances (such as the 3:1, 4:1, and 5:1) can also result in the excitation of inclinations, with mutual inclinations reaching  $\Delta i \sim 20 - 70^\circ$  in the simulations of Libert & Tsiganis (2009b), at least for low-mass inner planets and for one or both planets developing eccentricities  $e \gtrsim 0.4$ . Amongst systems believed to be in higher-order resonance, HD 60532 (3:1), HD 108874 (4:1) and HD 102272 (4:1) do not satisfy these requirements, and are likely to reside in co-planar resonances, as verified by numerical simulations.

**Lidov–Kozai oscillations** Large mutual inclinations can be generated by Lidov–Kozai oscillations (§10.10.6), as well as through planet–planet scattering (§10.10.4) and planetesimal-driven migration (§10.10.3). Whether any of the known systems are in a stable Lidov–Kozai resonant state, with mutual orbital inclinations of order  $\Delta i \sim 40 - 60^\circ$ , was investigated parametrically by Libert & Tsiganis (2009a). They found that four of the systems studied ( $\nu$  And, HD 12661, HD 74156, and HD 169830) could in principle be in Kozai resonance, provided that their mutual inclination is at least  $45^\circ$ . Direct astrometric determination of the mutual inclinations in  $\nu$  And by HST-FGS (§3.7, McArthur et al., 2010) gave  $\Delta i_{cd} = 29.9 \pm 1^\circ$ .

**The 1:1 resonance** A number of objects in the solar system move in 1:1 resonance orbits. They are examples of Lagrange’s celebrated solution to the restricted three-body problem, and generally satisfy the condition that

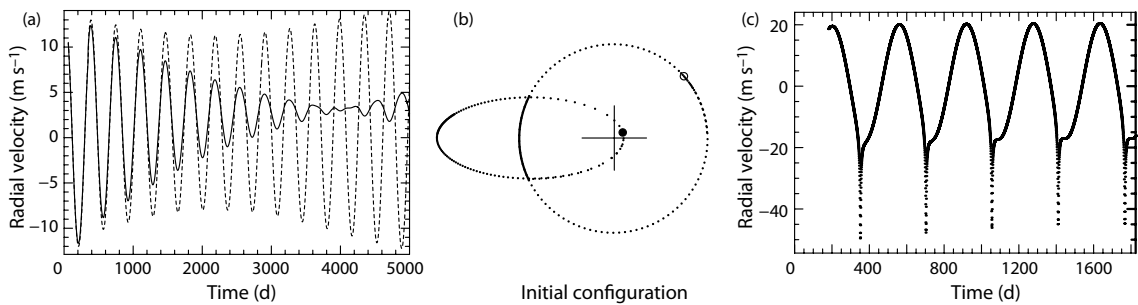


Figure 2.45: Theoretical 1:1 resonance orbits for equal mass planets: (a) synthetic radial velocity variations predicted for the tadpole-type (dotted) and horseshoe-type (solid) orbits; (b) initial configuration for the 1:1 eccentric resonance; solid lines indicate parts of the respective orbits swept out over 15% of the orbital period; (c) associated radial velocity variations for the case of eccentric resonance. From Laughlin & Chambers (2002, Figures 3, 4, 6), by permission of IOP Publishing/AAS.

the mass of the smallest is negligible compared with that of the other two (see box, page 74).

For the more general three-body problem, and in particular for two equal mass planets which share a time-averaged orbital period, Laughlin & Chambers (2002) identified a wide parameter space in which stable coorbital configurations exist (Figure 2.45).

**Possible orbits** These stable coorbital configurations fall into rather distinct regimes. In the first, the star and both planets participate in tadpole-like librations around the vertices of an equilateral triangle. The dynamics resembles that of Jupiter's Trojan asteroids, and the configuration is stable for mass ratios  $2M_p/(2M_p + M_*) < 0.03812$ . In the second regime, for larger perturbations, the planets execute symmetrical horseshoe-type orbits similar to those of Janus and Epimetheus. Stability analysis indicates that a pair of Saturn-mass planets could survive in this resonance over long periods (Figure 2.45a).

In practice, recognising such systems from the radial velocity data might be problematic, since the periodogram signal can be indistinguishable from that of a single planet in an eccentric orbit (Laughlin & Chambers, 2002), or from that of a system in 2:1 mean motion resonance (Goździewski & Konacki, 2006).

Their third configuration, described as *eccentric resonance*, is qualitatively distinct from Lagrange's solution (Figure 2.45b). One orbit starts as highly eccentric, the other is more nearly circular, the pericentres are aligned, and conjunctions occur near pericentre; the pair of planets then exchange angular momentum and eccentricity (in the case studied, with a periodicity of  $\sim 800$  yr). With appropriate initial conditions, they can avoid close encounters indefinitely. In this regime, the radial velocity variations are distinctive, perhaps recognisable by a single deviating measurement superposed on an otherwise sinusoidal pattern (Figure 2.45c). A similar configuration was found independently by Nauenberg (2002b). These eccentric resonances might arise from the same type of planet–planet interactions responsible for non-resonant high eccentricity systems.

The theoretical existence and properties of the various 1:1 resonance configurations (Hadjidemetriou et al., 2009) has led some investigations to consider them as alternative models for certain specific systems (e.g. Érdi et al., 2007), in particular in cases where long-term orbit integration has identified dominant instabilities.

Goździewski & Konacki (2006) examined the long-term stability of HD 128311 (§2.12.4), searching for alternative 2:1 res-

onances using a genetic algorithm, and examining their long-term stability using MEGNO. They also searched for 1:1 resonances consistent with the observed radial velocity variations, and identified extended zones of stability in which such a system would survive (Figure 2.46). They used the term ‘Trojan planets’ for all 1:1 mean motion resonances, including the eccentric resonance configurations identified by Laughlin & Chambers (2002), i.e. not only for the Lagrange-type solutions, but also for those with similar semi-major axes, but possibly with large relative inclinations and time-varying eccentricities.

In the multiple planet system  $\mu$  Ara studied by Pepe et al. (2007) one of their solutions, located using a genetic algorithm search, gave an inner planet at 9.64 d, an outer planet at 2741 d, and with an intermediate pair of Trojan planets in a 1:1 mean motion resonance. The solution was discarded as a result of its high dynamical instability; orbit integration indicating that it would be disrupted in less than 100 years.

Schwarz et al. (2007a,b,c) demonstrated the stability of terrestrial Trojan planets in resonance with a giant planet in the habitable zone for a number of systems.

The formation of a hypothetical terrestrial-type body at the Lagrange points of a giant exoplanet has been studied using an N-body code by Beaugé et al. (2007). Although such planets may form *in situ*, the accretion process is inefficient, and the mass of the final planet never exceeds  $\sim 0.6M_{\oplus}$ .

**Retrograde resonances** Systems with multiple planets are generally considered to revolve in the same direction around their respective system barycentres, and most radial velocity orbit elements are derived assuming *prograde* or *regular* orbits, i.e. all orbiting in the same direction. Such behaviour is expected, at least for unperturbed states, according to planet formation theories.

The theoretical existence and dynamical stability of *retrograde* mean motion resonances, i.e. with one planet counter-revolving with respect to the other in a two-planet system, or to all other planets in a multiple planet system, has been investigated and demonstrated (Gayon & Bois, 2008a,b; Gayon et al., 2009).

**Formation of retrograde resonances** A planet might conceivably be found in a retrograde mean motion resonance either as a result of capture of a pre-existing free-floating planet directly into a retrograde orbit, or through (violent) dynamical



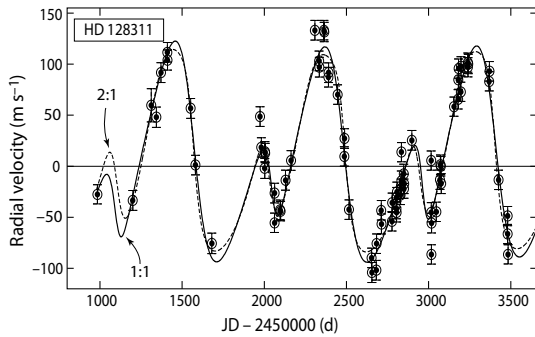


Figure 2.46: The two-planet system HD 128311, showing radial velocity curves for the best-fit solutions corresponding to the 2:1 (dashed) and 1:1 (solid) mean motion resonances. Both curves give an rms of  $15 \text{ m s}^{-1}$ . Error bars include the stellar jitter of  $9 \text{ m s}^{-1}$ . From Goździewski & Konacki (2006, Figure 4), by permission of IOP Publishing/AAS.

evolution as a result of planet–planet interactions. The slingshot effects seen in the simulations of Nagasawa et al. (2008) show that close-in planets, some in retrograde motion as a result of Lidov–Kozai resonances, may indeed result.

In the solar system, a small number of asteroids, a number of asteroid-size planetary moons, and Triton (the largest of Neptune’s moons) have retrograde orbits.

Gayon & Bois (2008a) used the genetic algorithm PIKAIA and the fast-chaos indicator MEGNO to search for stable 2:1 retrograde resonant configurations for HD 73526, consistent with the published initial conditions. They found prominent stability islands, which occur when the apsidal longitudes of the two orbits precess at the same average rate, albeit with complex structure, and even though they do not precess in the same direction. The resulting radial velocity curve is very similar to that given by the prograde solutions of Tinney et al. (2006) and Sándor et al. (2007a).

Similar counter-revolving solutions have been investigated by Gayon-Markt & Bois (2009) for eight compact multi-planet systems. Their results suggest that six of them (HD 69830, HD 73526, HD 108874, HD 128311, HD 155358 and HD 202206) could be dynamically regulated by such a configuration.

**Retrograde packing** Systems with retrograde planets can be packed substantially more closely than prograde systems with an equal number of planets (Smith & Lissauer, 2009).

**Resonant planets disguised as single** Various studies have shown how different orbital architectures, such as planet pairs near a 2:1 orbital resonance, or even a pair of (Trojan) planets in a hypothetical co-orbital motion, can be difficult to distinguish from a single (eccentric) planet (Giuppone et al., 2012a; Dobrovolskis, 2013a, 2015b; Leleu et al., 2015).

A specific example is the case of HD 27894, originally discovered as a single-planet system (Moutou et al., 2005a), with evidence that the eccentric orbit might be a 2:1 resonant pair (Kürster et al., 2015), followed by evidence for an inner resonant pair and an outer eccentric planet (Trifonov et al., 2017).

### 2.12.5 Interacting two-planet systems

A number of systems contain two giant planets in which planet–planet interactions are significant. These include: HD 12661 (Goździewski & Maciejewski, 2003); HD 14810 (Wright et al., 2009b); HD 155358 (Cochran et al., 2007); HD 169830 (Goździewski & Konacki, 2004); and HD 183263 (Wright et al., 2009b).

### 2.12.6 Non-interacting two-planet systems

A number of systems contain planet pairs with very large ratios of their orbital periods (sometimes referred to as ‘hierarchical’, but see the footnote on page 511), which are therefore unlikely to be interacting. These include: HD 11964 with  $P = 38 \text{ d}$  and  $5.3 \text{ yr}$  (Wright et al., 2009b); HD 68988 with  $P = 6.3 \text{ d}$  and  $11\text{--}60 \text{ yr}$  (Wright et al., 2007); HD 168443 with  $P = 58 \text{ d}$  and  $4.8 \text{ yr}$  (Marcy et al., 2001b); HD 187123 with  $P = 3 \text{ d}$  and  $10.5 \text{ yr}$  (Wright et al., 2009b); HD 190360 with  $P = 17.1 \text{ d}$  and  $8.0 \text{ yr}$  (Vogt et al., 2005); HD 217107 with  $P = 7.1 \text{ d}$  and  $11.7 \text{ yr}$  (Wright et al., 2009b); and HD 38529 with  $P = 14.3 \text{ d}$  and  $5.9 \text{ yr}$  (Fischer et al., 2003b).

### 2.12.7 Super-Earth systems

Systems comprising only low-mass planets are being discovered in greater numbers as radial velocity accuracies improve. The first three discovered were:

HD 69830: the triple Neptune system with  $P \sim 9, 32$ , and  $200 \text{ d}$  (Lovis et al., 2006). The outer planet is located near the inner edge of the habitable zone. Beichman et al. (2005a) reported Spitzer photometry and spectroscopy, which shows an infrared excess characteristic of a large cloud of fine silicate dust within a few au of the star, suggestive of a large asteroid belt.

GJ 581: a five- or six-planet system (Bonfils et al., 2005b; Udry et al., 2007; Vogt et al., 2010a), with some lying within, or close to the inner and outer edges, of the star’s habitable zone (§11.7.4). Further details are given below.

HD 40307: the third triple super-Earth system, with masses  $4.2, 6.9$ , and  $9.2 M_{\oplus}$  (Mayor et al., 2009b).

**GJ 581** GJ 581 is a nearby (6.27 pc) M3V dwarf. Radial velocity data, including 119 measurements over  $4.3 \text{ yr}$  from HARPS, and 122 over  $11 \text{ yr}$  from HIRES (Bonfils et al., 2005b; Udry et al., 2007; Mayor et al., 2009a; Vogt et al., 2010a) suggest the presence of up to six planets (not all of which have been independently confirmed to date), listed in Table 2.9, and illustrated schematically in Figure 2.47. Dynamical stability (Beust et al., 2008), issues of aliasing (Dawson & Fabrycky, 2010), and the possibility of hidden and stable orbits (Zollinger & Armstrong, 2009; Anglada-Escudé et al., 2010a) have been studied.

Udry et al. (2007) originally suggested that planet c ( $M_{\text{p}} \sin i = 5.1 M_{\oplus}$ ,  $P = 12.9 \text{ d}$ ) lies close to the inner edge of the habitable zone, while planet d ( $M_{\text{p}} \sin i = 8.3 M_{\oplus}$ ,  $P = 83.4 \text{ d}$ ) lies close to its outer edge. The original estimate of the equilibrium temperature of planet c ( $T_{\text{eq}} \sim 320 \text{ K}$ , assuming a Bond albedo  $A_{\text{B}} \sim 0.5$ ) was revised by later studies, but

Table 2.9: The planets of GJ 581, ordered by increasing semi-major axis. Data are from Vogt et al. (2010a).

Planet	$M_p \sin i$ ( $M_\oplus$ )	$a$ (au)	$P$ (d)
e	1.7	0.028	3.15
b	15.6	0.041	5.37
c	5.6	0.073	12.92
g	3.1	0.146	36.56
d	5.6	0.218	66.87
f	7.0	0.758	433

with the emerging consensus that planets c and d could nevertheless support habitability depending on their atmospheres, and whether they are tidally locked (Selsis et al., 2007; von Bloh et al., 2007a; Chylek & Perez, 2007).

Further data and analysis by Vogt et al. (2010a) suggests that a proposed sixth planet, GJ 581 g ( $M_p \sin i = 3.1 M_\oplus$ ,  $P = 36.6$  d,  $a = 0.146$  au,  $e = 0$ ) could place it in the middle of the star's habitable zone. The radius of GJ 581 g is estimated as  $1.3 - 1.5 R_\oplus$  if primarily composed of magnesium silicates,  $1.7 - 2 R_\oplus$  if predominantly  $H_2O$ -ice, and with all radii smaller by 20% if it is significantly differentiated. The mass and radius together imply a surface gravity  $\sim 1.1 - 1.7 g_\oplus$ .

Its estimated  $T_{eq} \sim 209 - 228$  K, depending on  $A_B$ , satisfies the conditions necessary for habitability of  $T_{eq} \leq 270$  K derived by Selsis et al. (2007). The actual surface temperature is expected to be higher than  $T_{eq}$ . For Earth ( $T_{eq} \sim 255$  K), atmospheric greenhouse heating results in a mean surface temperature  $T_s \sim 288$  K. For a comparable or more massive atmosphere, greenhouse heating, combined with its probable synchronous-rotation (tidal locking), will result in higher surface temperature, plausibly implying the presence of liquid water.

**Stability of habitable zone systems** Numerous investigations have been carried out to examine the stability of planets which might exist in the habitable zones of known systems (§11.7.1). Using fast indicators of stability or chaos, stability maps can help to establish, for example, whether and where Earth-like planets could exist in systems having one giant planet (Figure 2.48).

Orbits of terrestrial-type planets within the habitable zone have been classified as fully stable if no mean motion resonance exists within that zone, partially stable if only a few resonances exist, marginally stable if many resonances exist, and very unstable if the region is found to be strongly chaotic (Sándor et al., 2007b).

### 2.13 Binary and multiple stars

Early radial velocity surveys tended to exclude spectroscopic and visual binary stars with separations below 2–6 arcsec because of problems of light contamination from the other component at the spectrograph entrance (Udry et al., 2000; Perrier et al., 2003; Marcy et al., 2005b; Jones et al., 2006b). This resulted in limited or biased surveys for binary star separations  $\leq 100 - 200$  au.

At larger separations, viz. for visual binaries with separations  $\geq 100$  au, circumstellar planet searches can treat the targets as distinct single stars, and such surveys

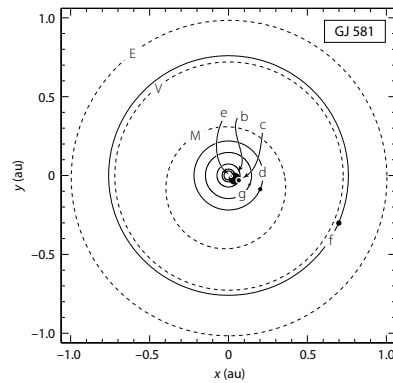


Figure 2.47: View of the GJ 581 system from above, with coordinates in au. Planets, shown with a circle size proportional to mass, are from inner to outer: e, b, c, g, d, f, of orbital period 3.1, 5.4, 12.9, 36.6, 66.9, 433 d respectively, and mass ( $M_p \sin i$ ) 1.7, 15.6, 5.6, 3.1, 5.6, 7.0  $M_\oplus$  respectively. The orbits of M (Mercury), V (Venus), and E (Earth) are shown to the same scale. From Vogt et al. (2010a, Figure 6), by permission of IOP Publishing/AAS.

have faced limited technical difficulty (Gratton et al., 2003; Desidera & Barbieri, 2007; Toyota et al., 2009).

Observational confirmation that giant planets existed orbiting one component of a spectroscopic binary star came with the discoveries of GJ 86 Ab (Queloz et al., 2000b) with its white dwarf companion, and  $\gamma$  Cep Ab (Hatzes et al., 2003a), a binary with  $P = 57$  yr, with the planet orbiting the primary with  $P = 2.48$  yr.

The growing interest in exploring broader planetary domains as a way of constraining formation models has led to some more recent surveys preferentially including, rather than excluding, binary systems (Table 2.6).

Amongst specific radial velocity surveys focusing on binaries are a sample of 101 single-lined spectroscopic binaries (SB1) with  $P > 1.5$  yr, selected on the basis of the earlier CORAVEL surveys (Duquennoy & Mayor, 1991; Halbwachs et al., 2003). A programme to supplement the original CORAVEL data with 10–15 additional high-precision measurements of each system, using ELODIE in the north and CORALIE in the south, was initiated in 2001 (Eggenberger, 2010). Analysis employs the spectral deconvolution programme TODCOR. No promising candidates have been reported, and constraints indicate that  $\leq 20\%$  of SB1 systems host a short-period,  $P < 40$  d circumprimary giant ( $M_p \sin i \geq 0.5 M_J$ ) planet.

No extensive surveys have yet been undertaken for double-lined spectroscopic binaries (SB2) (Eggenberger, 2010). The principal reason for this is related to the problem of wavelength calibration: the standard technique using iodine cells (§2.3) is only applicable to single stars, and the time-varying spectra of SB2s cannot provide the template spectrum required by Equation 2.45. A modified procedure applicable to SB2s, using interleaved observations with and without the iodine cell, has been described by Konacki (2005b).

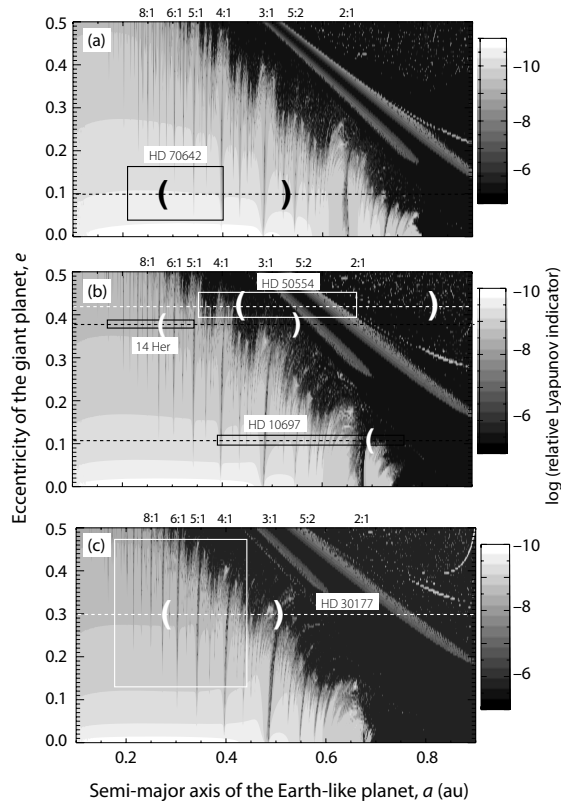


Figure 2.48: Stability maps, computed by the method of relative Lyapunov indicators, for orbits of possible habitable-zone planets interior to the orbit of a known giant planet, for various values of mass ratios  $\mu = M_p / (M_\star + M_p)$ , where  $M_p$  is the mass of the giant planet, and the mass of the hypothetical terrestrial-type planet is negligible: (a)  $\mu = 0.002$ , (b)  $\mu = 0.005$ , (c)  $\mu = 0.009$ . The habitable zones corresponding to the star's zero-age main sequence luminosity are indicated by elongated rectangles, whose heights correspond to the uncertainty on the giant planet's eccentricity, while the current habitable zones are indicated by parentheses. Positions of mean motion resonances are indicated. In (c), for example, the eccentricity of the giant planet in the HD 30177 system is highly uncertain. The present habitable zone is strongly chaotic for large values of  $e$ , while its inner part is marginally stable for small  $e$ . From Sándor et al. (2007b, Figures 7, 9 and 10), © Oxford University Press.

**Other surveys for binary identification** In parallel, the fraction of planets known to reside in binary systems has risen as a result of searches for common proper motion companions to known planet-hosting stars.

Other searches for planets around binary systems include transit studies of eclipsing binaries (§6.3) which may allow the detection of transiting circumstellar or circumbinary planets (Deeg et al., 1998; Doyle et al., 2000; Ofir, 2008), or Trojan planets (Caton et al., 2000), and of non-transiting giant planets in circumbinary orbits through eclipse timing. The latter has resulted in the discovery of a few circumbinary systems (§4.4).

### 2.13.1 Present inventory

By late 2010, more than 50 planets had been found associated with binary or multiple stars (Eggenberger et al., 2004b; Eggenberger, 2010). Although most were giants orbiting the primary, with projected separations in the range 20–12 000 au, one possibly circumbinary planet, HD 202206, had been reported (Correia et al., 2005).

More recent statistics of planetary systems discovered orbiting binary stars are given by Crepp et al. (2016), and their distribution as a function of binary separation are given in their Figure 2. Few small-separation systems have been searched for with the radial velocity technique because existing spectrometers are seeing-limited. A diffraction-limited Doppler spectrometer for the Large Binocular Telescope (LBT), iLocator, to measure close-in system, is described in Section 2.6.6.

At small binary separations,  $\lesssim 100$  au, only a small number of planets have been found, and giant planets may be rarer in these systems than around wider separation binaries or single stars (e.g. Bonavita & Desidera, 2007). This may be consistent with studies which suggest that giant planet formation is inhibited under the influence of a nearby orbiting stellar companion (Nelson, 2000; Mayer et al., 2005; Thébault et al., 2006).

At the smallest binary separations,  $\lesssim 20$  au, the absence of circumstellar planets is consistent with the idea that giant planet formation in these systems is suppressed (Nelson, 2000; Thébault et al., 2004; Mayer et al., 2005; Thébault et al., 2006; Boss, 2006a), although Doppler surveys to confirm this remain incomplete.

**Properties** Roell et al. (2012) estimated that, as of 2012, 57 exoplanet (radial velocity or transit) host stars have a *stellar* companion. The resulting multiplicity rate of (at least) 12% for exoplanet host stars is about four times smaller than that of solar-like stars in general. The mass and the number of planets in these multiple stellar systems depends on the separation between the two stellar components, e.g. the planetary mass decreases with an increasing stellar separation.

Zucker & Mazeh (2002) suggested that planets in binaries follow a different mass–period relation than those orbiting single stars, with the most massive short-period planets being found in binary or multiple systems. Later studies showed a lower significance (Eggenberger et al., 2004b; Desidera & Barbieri, 2007; Mugrauer et al., 2007; Eggenberger, 2010), and the most recent distributions (Figure 2.49a) reveal mixed evidence for such an effect. Meanwhile, short period ( $P < 50$  d) planets around binary stars do appear to have smaller eccentricities,  $e \lesssim 0.05$ , than around single stars (Figure 2.49b).

Still based on somewhat limited statistics, the few planets with the highest eccentricities,  $e > 0.8$ , tend to be accompanied by a stellar or brown dwarf companion (Tamuz et al., 2008), a correlation that may extend to lower masses (Ribas & Miralda-Escudé, 2007). This has been taken to support the idea of eccentricities being excited by the Kozai mechanism, in which hierarchical triple systems with high relative inclinations cause large-amplitude periodic oscillations of the eccentricity of the inner pair (Holman et al., 1997; Innanen et al., 1997; Mazeh et al., 1997; Ford et al., 2000b; Wu & Murray, 2003; Takeda & Rasio, 2005; Moutou et al., 2009a).

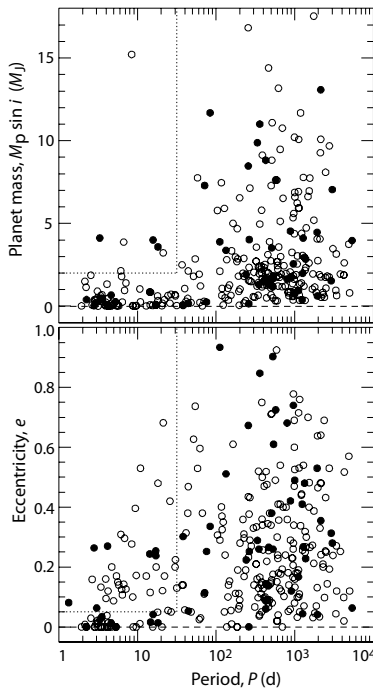


Figure 2.49: Planets detected from radial velocities (317 planets from *exoplanets.org*, 2010–11–01), with those orbiting single stars shown as open circles, and those in binary or multiple systems as filled circles. Top: mass ( $M_p \sin i$ ) versus orbital period. Bottom: eccentricity versus period. Dashed regions correspond to those delineated by Eggenberger (2010, Figure 1).

The coupling of Lidov–Kozai oscillation with tidal friction, also referred to as Lidov–Kozai migration, might also lead to short-period planets preferentially following nearly circular orbits (Figure 2.49b). In multiple systems this mechanism may be more effective than type II migration in bringing massive planets close to their host stars. This may also explain why the most massive short-period planets are found in binary or multiple systems (Takeda & Rasio, 2006; Fabrycky & Tremaine, 2007).

### 2.13.2 Specific examples

**$\gamma$  Cep** The binary star system  $\gamma$  Cep harbours a stable giant planet orbiting the primary star at a distance some one tenth of the stellar separation (Hatzes et al., 2003a). The primary and secondary stars, of masses 1.6 and  $0.4M_\odot$ , are separated by 18.5 au ( $P \sim 57$  yr,  $e = 0.36$ ), with the planet of mass  $1.7M_J$  orbiting the primary with  $a = 2.13$  au,  $P = 2.5$  yr,  $e = 0.12$ .

Numerical integrations as a function of  $a_b$ ,  $e_b$ , and  $i_b$  (the inclination of the planet with respect to the stellar binary) by Haghighipour (2006), show that the planet orbit is stable for values of the binary eccentricity  $0.2 \leq e_b \leq 0.45$ , with the system becoming unstable within a few thousand years for  $e_b > 0.5$ . Within the stable range of orbital eccentricity, the planet remains stable for  $i_b < 40^\circ$ , becoming unstable within a few thousand years for  $i_b > 40^\circ$ . For large values of the inclination, the system may be locked in a Kozai resonance (Haghighipour, 2004). The stability map for test particles interior to the planet orbit show complex stability patterns influenced by mean motion resonances (Figure 2.50).

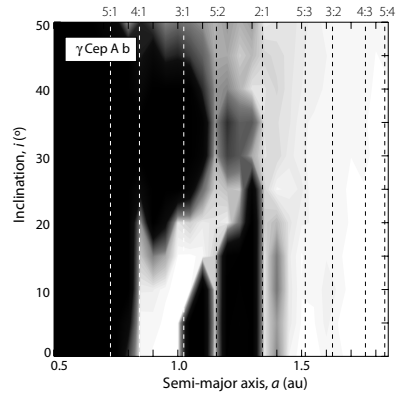


Figure 2.50: Stability of test particles interior to the planet  $\gamma$  Cep Ab, for the co-planar case  $i_b = 0$ . Stability is indicated by the test particle’s survival time averaged over longitudes and normalised to 1 Myr. Lighter regions are unstable, darker regions indicate higher stability. Dashed vertical lines are nominal locations of mean motion resonances with  $\gamma$  Cep Ab. From Verrier & Evans (2006, Figure 2), © Oxford University Press.

Various studies of planet formation in this system have been made (Kley & Nelson, 2008; Jang-Condell et al., 2008; Paardekooper & Leinhardt, 2010; Beaugé et al., 2010; Giuppone et al., 2011; Müller & Kley, 2012; Martí & Beaugé, 2012; Rafikov, 2013b; Rafikov & Silsbee, 2015b; Funk et al., 2015).

**16 Cyg B** The planet around 16 Cyg B has a highly eccentric orbit,  $e \sim 0.7$ . 16 Cyg B is one component of a wide-separation binary whose eccentricity is itself large,  $e > 0.54$ . The orbital period of the binary star is long and difficult to measure accurately, but from astrometry over 170 years is estimated to be  $>18\,000$  yr (Hauser & Marcy, 1999). 16 Cyg A may also have a close stellar companion (Patience et al., 2002).

The system is an interesting case for planetary formation theories, which try to explain the large eccentricities in binary systems as a result of gravitational perturbations by the other stellar component, here 16 Cyg A. If the planet was originally formed in a circular orbit, with an orbital plane inclined to that of the stellar binary by  $>45^\circ$ , then the planet orbit is predicted to oscillate chaotically between high- and low-eccentricity states, on time scales of  $10^7 - 10^{10}$  yr (Holman et al., 1997; Mazeh et al., 1997; Hauser & Marcy, 1999; Plávalová & Solovaya, 2013). Further planets with  $M_p \sim M_J$  within 30 au would require this conclusion to be revisited.

**HD 188753** Some controversy surrounds this triple system (Mazeh et al., 2009b), comprising a 155 d spectroscopy binary (HD 188753B) in a 25.7-yr orbit ( $a = 12.3$  au) about the primary (HD 188753A). Konacki (2005a) reported a  $3.35 \pm 1.1M_J$  planet around the primary, based on  $10 \text{ m s}^{-1}$  accuracy Keck–HIRES data, unconfirmed by Eggenberger et al. (2007b).

According to theoretical studies, the pericentre distance of the AB pair is too small to have allowed giant planet formation. Modeling by Jang-Condell (2007) has shown that the circumstellar disk around the primary would have been truncated at around 1.5–2.7 au, leaving insufficient material, and in any case too hot, for a Jovian planet to have formed *in situ*. Alternative formation mechanisms were forthcoming, in particular proposing that the primary could have acquired the planet through interactions within an open star cluster that has now dissolved (Pfahl, 2005; Portegies Zwart & McMillan, 2005).

# Astrometry

ASTROMETRY CONCERNS THE MEASUREMENT of positions and motions of solar system bodies, stars within the Galaxy and, in principle, galaxies and clusters. Traditionally, an important goal has been to determine stellar parallaxes and proper motions, which are of crucial importance in understanding host star properties.

In the present context, repeated high-accuracy astrometry also aims to determine the transverse component of the displacement of the host star due to the gravitational perturbation of an orbiting planet. This dynamical manifestation of their gravitational influence in the *plane of the sky* is closely related to radial velocity measurements, which are sensitive to the corresponding photocentre displacement *along* the line-of-sight.

Current best accuracies, of  $\sim 1$  mas achieved with the Hipparcos mission, and with the HST–Fine Guidance Sensors, only just touch the regime where displacements of star positions due to orbiting planets can be detected. As of the end of 2017, only one single sub-stellar companion, of  $28M_J$ , appears in the NASA Exoplanet Archive as discovered by astrometry.

The panorama is changing with Gaia, launched in 2013, and which is measuring more than  $10^9$  stars to  $V = 20 - 21$  mag, at accuracies of  $\sim 20 - 25 \mu\text{as}$  at 15 mag. This is expected to lead to the discovery of several thousand planetary systems, providing absolute orbits, planet masses without the  $\sin i$  ambiguity, and information on co-planarity.

## 3.1 Introduction

The path of a star orbiting the star–planet barycentre appears projected on the plane of the sky as an ellipse with angular semi-major axis  $\alpha$  given by

$$\alpha = \frac{M_p}{M_\star + M_p} a \approx \frac{M_p}{M_\star} a \quad (3.1)$$

$$\equiv \left( \frac{M_p}{M_\star} \right) \left( \frac{a}{1 \text{ au}} \right) \left( \frac{d}{1 \text{ pc}} \right)^{-1} \text{ arcsec}, \quad (3.2)$$

where  $a$  is the semi-major axis of the planet orbit (here assumed circular),  $d$  is the distance, and  $M_p$  (planet

and  $M_\star$  (star) are in common units. The former expresses  $\alpha$  in linear measure (e.g. in au if  $a$  is in au, and the approximation holding for  $M_p \ll M_\star$ ), while the latter equivalently expresses it in angular measure through the definition of the parsec.

This *astrometric signature*  $\alpha$  is the observable for astrometric planet detection, and is proportional to both  $M_p$  and  $a$ , and inversely to  $d$ . Astrometry is therefore particularly sensitive to long orbital periods ( $P \gtrsim 1$  yr), applying equally to hot or rapidly rotating stars. The technique aims to discern an orbiting planet on top of the two other classical astrometric effects: the linear path of the system’s barycentre (its proper motion) combined with the reflex motion (its parallax) resulting from the Earth’s orbital motion around the Sun (Figure 3.1).

**Size of the effect** The size of the effect calculated for the planets known at the end of 2017 is shown in Figure 3.9, and some representative values are given in Table 3.1. The accuracy required to detect planets astrometrically is typically sub-mas, although it would reach a few mas for planets of  $M_p \sim 1M_J$  orbiting nearby solar-mass stars. For the 600 radial velocity planets with the data necessary to estimate  $\alpha$ , the median value is  $\sim 20 \mu\text{as}$ , while for the corresponding 350 transiting planets it is only  $\sim 0.1 \mu\text{as}$ .

The accuracy required for the detection of planets in the habitable zone of long-lived main sequence stars (spectral type A5 and later) can be estimated as follows. The mean star–planet separation of the habitable zone for a star of luminosity  $L$  has been estimated as  $a \sim (L/L_\odot)^{1/2}$  au (Kasting et al., 1993). Over this mass range,  $\sim 0.2 - 2M_\odot$ ,  $L \propto M_\star^{4.5}$  (Torres et al., 2010a), so that  $\alpha \propto M_\star^{2.25}$  and hence

$$\alpha \approx 3 \mu\text{au} \left( \frac{M_p}{M_\oplus} \right) \left( \frac{M_\star}{M_\odot} \right)^{1.25}. \quad (3.3)$$

Accordingly, for a  $1M_\oplus$  planet orbiting a main sequence star,  $\alpha$  ranges from about  $2.3 \mu\text{au}$  for spectral type K0V, up to about  $7 \mu\text{au}$  for A5V. Gould et al. (2003a) similarly argued that A and F stars constitute the majority of viable targets for such astrometric searches.

Table 3.1: Astrometric signature for a  $1M_{\odot}$  star, and a variety of star distance  $d$ , planet mass  $M_p$ , and semi-major axis  $a$ .

Type	$d$ (pc)	$M_p$	$a$ (au)	$\alpha$ ( $\mu\text{as}$ )
Jupiter	10	$1M_J$	5	500.
"	100	"	"	50.
Hot Jupiter	10	$1M_J$	0.01	1.
"	100	"	"	0.1
Earth	10	$1M_{\oplus}$	1	0.3
"	100	"	"	0.03

## 3.2 Astrometric accuracy from ground

### 3.2.1 Single aperture

The theoretical photon-noise limited positional error for a monolithic telescope is given by (Lindgren, 1978)

$$\sigma_{\text{ph}} = \frac{\lambda}{4\pi D} \frac{1}{S/N}, \quad (3.4)$$

where  $D$  is the telescope diameter,  $\lambda$  the wavelength, and  $S/N$  the signal-to-noise. For  $V = 15$  mag,  $\lambda = 600$  nm,  $D = 10$  m, a system throughput of  $\epsilon = 0.4$ , and an integration time of 1 h, the resulting positional error due to photon noise alone is  $\sigma_{\text{ph}} \sim 30 \mu\text{as}$ . Mainly as a result of atmospheric turbulence and differential chromatic refraction, however, even the best astrometric accuracies achieved on the ground currently fall far short of this theoretical performance.

While astrometry has developed over two millennia (Perryman, 2012), an understanding of the accuracy limits of narrow-angle astrometry has evolved considerably over the last three decades. Until the 1970s, long-focus telescopes equipped with photographic plates were used for accurate narrow-angle astrometric measurements. Analyses of image centroids yielded measurements at the 20–30 mas level (Harrington & Dahn, 1980). The introduction of CCDs, and the Ronchi ruling photometer (Gatewood, 1987), eliminated plate-specific error sources to the point that atmospheric turbulence became a dominant source of error.

For small angular separations,  $\lesssim 1$  arcmin, the time-averaged precision with which the angle between two stars near the zenith can be measured is reasonably consistent with atmospheric turbulence models (Lindgren, 1980, eqn 35a)

$$\sigma_{\delta} \approx 540 D^{-\frac{2}{3}} \theta t^{-\frac{1}{2}} \text{ arcsec}, \quad (3.5)$$

where  $\theta$  is their angular separation in rad,  $D$  the telescope diameter in m, and  $t$  the integration time in s; in these units, the formula is valid for  $\theta \ll d/4300$ . The numerical factor is obtained from the (assumed Hufnagel) phase-structure function describing the atmospheric (Kolmogorov-like) turbulence for the atmospheric seeing and wind-speed profiles typical of a good site. Values of  $\theta = 1$  arcmin,  $D = 1$  m, and  $t = 1$  h lead

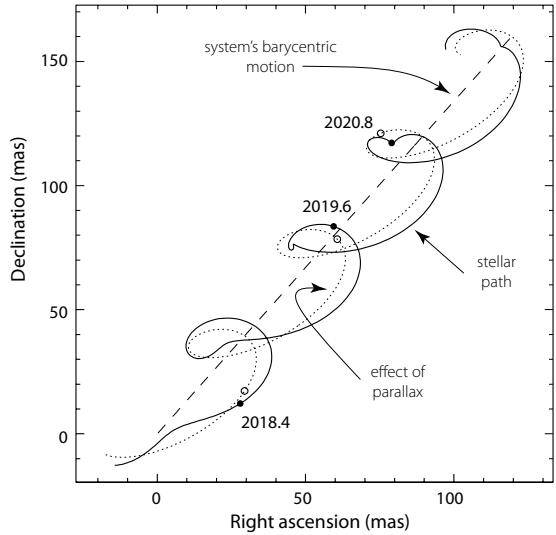


Figure 3.1: Schematic of the path on the sky of a star at  $d = 50$  pc, with a proper motion of  $50 \text{ mas yr}^{-1}$ , and orbited by a planet of  $M_p = 15 M_J$ ,  $e = 0.2$ , and  $a = 0.6$  au. The straight dashed line shows the system's barycentric motion viewed from the solar system barycentre. The dotted line shows the effect of parallax (the Earth's orbital motion around the Sun, with a period of 1 year). The solid line shows the motion of the star as a result of the orbiting planet, the effect magnified by  $\times 30$  for visibility. Labels indicate (arbitrary) times in years.

to  $\sigma_{\delta} \approx 3$  mas, in reasonable agreement with the accuracies reported for long-focus telescopes with star separations up to a few arcmin (e.g. Gatewood, 1987; Han, 1989; Monet et al., 1992).

With several reference stars, theoretical estimates give a further improvement, variously described by

$$\sigma_{\delta} \propto D^{-1} \theta^{\frac{4}{3}} t^{-\frac{1}{2}} \quad \text{Lindgren (1980)}, \quad (3.6)$$

$$\sigma_{\delta} \propto D^{-\frac{3}{2}} \theta^{\frac{11}{6}} t^{-\frac{1}{2}} \quad \text{Lazorenko (2002)}. \quad (3.7)$$

Such predictions are substantially confirmed by the results of, e.g., Pravdo & Shaklan (1996).

Further innovative approaches to observation and measurement continue to be developed. Lazorenko & Lazorenko (2004) considered apodisation of the entrance pupil, and an improved symmetry treatment of the reference field (by assigning specific weights to each reference star), leading to their modified and more general theoretical expression for the differential astrometric error due to the atmosphere

$$\sigma_{\delta} \propto D^{-\frac{k}{2} + \frac{1}{3}} \theta^{\frac{k\mu}{2}} t^{-\frac{1}{2}}. \quad (3.8)$$

Here,  $2 \leq k \leq (8N+1)^{1/2} - 1$  is determined by the number of reference objects  $N$ , and  $\mu \leq 1$  is a term dependent on  $k$  and the magnitude and distribution of the reference stars; the expression reduces to Equation 3.5 for  $N = 1$  (i.e.  $k = 2$ ). The reference field forms a 'virtual net filter' which attenuates the image motion spectrum.

**Early investigations:** Anomalies in the astrometric orbit of 70 Oph were reported as early as 1855. Captain W.S. Jacob, at the East India Company's Madras Observatory, reported that such anomalies made it 'highly probable' that the system contained a planetary body (Jacob, 1855). Subsequently, the American, Thomas See, was involved in measuring binary star orbits at the Lowell 24-inch telescope (near Mexico City) in the 1890s (Sherrill, 1999). In a series of papers (See, 1895, 1896a,b, 1897), he also inferred the presence of a dark body in orbit around it. Although See didn't explicitly claim the companion to be a planet, he remarked (See, 1895) '*Since August 20, when I first announced to you the existence of peculiar anomalies in the motion of the companion of [70 Oph], I have succeeded in showing conclusively that the system is perturbed by an unseen body... I find that the dark body has a period of approximately forty years*'. The orbit was criticised as unstable by Moulton (1899).

Holmberg (1938) reported other early investigations of the astrometric manifestations of planets. The abstract reads '*In the present paper modern trigonometric parallax observations are investigated. It appears that the residuals of these observations are not always distributed at random. Many parallax stars show periodic displacements. These effects probably are to be explained as perturbations caused by invisible companions. Since the amplitudes of the orbital motions are very small, the masses of the companions will generally be very small, too. Thus Proxima Cen probably has a companion, the mass of which is only some few times larger than the mass of Jupiter. A preliminary investigation gives the result that 25% of the total number of parallax stars may have invisible companions.*' Presumably, all that Holmberg saw was noise, but it nevertheless shows how, already in the 1930s, some understood the issues and made efforts to find exoplanets.

Two discoveries of planet-like companions from astrometric measurements of long-term time-series photographic plates were announced in 1943: companions of  $10M_J$  for 70 Oph by Reuyl & Holmberg (1943), and  $16M_J$  for 61 Cyg by Strand (1943). Strand was unequivocal: '*The only solution which will satisfy the observed motions gives the remarkably small mass of... 16 times that of Jupiter... Thus planetary motion has been found outside the solar system.*' The results were interpreted as supporting theories of the origin of the solar system (Alfvén, 1943) and speculations on the frequency of planetary systems (Jeans, 1943). Struve (1952) mentioned the merits of planet searches using radial-velocities, transit photometry, and astrometry, stating that '*one of the burning questions of astronomy deals with the frequency of planet-like bodies in the Galaxy which belong to stars other than the Sun*'.

Planets around 61 Cyg and 70 Oph were excluded by Heintz (1978b). But lengthy disputes surrounded extensive ground-based observations of Barnard's star, for which two planetary mass bodies ( $0.7$  and  $0.5 M_J$ ) with periods of 12 and 20 years were proposed (e.g. van de Kamp, 1963, 1982; Gatewood & Eichhorn, 1973; Croswell, 1988) and Lalande 21185 (e.g. Lippincott, 1960; Hershey & Lippincott, 1982; Gatewood et al., 1992; Gatewood, 1996). Doppler monitoring over 25 yr between 1987–2012 excludes such companions to Barnard's star, with the possible exception of strictly face-on orbits (Choi et al., 2013a).

Other early discussions of ground-based astrometric observations related to planet detection include van de Kamp (1967); Black (1980b,a); Black & Brunk (1980); Black & Scargle (1982); Black (1985) and Gatewood (1987). In presumably the earliest discussions of space astrometry, Couteau & Pecker (1964) considered both binary stars, and the search for planetary systems. An astrometric search for Jupiter-like companions to nearby stars using the Hipparcos data was suggested by Gliese (1982).

Formally, this leads to errors  $\leq 100 \mu\text{as}$  for 10-m telescopes (very good seeing,  $t \sim 600$  s). Narrow-field adaptive optics imagers on Palomar and VLT, have demonstrated short-term 100–300  $\mu\text{as}$  precision (Neuhäuser et al., 2007b; Lazorenko, 2006; Lazorenko et al., 2007; Röhl et al., 2008; Cameron et al., 2009). Multi-conjugate adaptive optics imaging at the VLT (MCAO, using VLT-MAD) has reached relative positional precision of  $\sim 1$  mas in ground-layer and two-layer measurements in the globular clusters 47 Tuc and NGC 6388 respectively (Meyer et al., 2011).

Lazorenko (2006) reported VLT-FORS2 positional accuracies  $\sim 300 \mu\text{as}$  (for  $R = 16$  mag and  $t = 17$  s with  $0.55$  arcsec seeing), dominated by  $\sim 250 \mu\text{as}$  centroiding errors. Under certain circumstances, positional precision as small as  $25 \mu\text{as}$  over six years has been claimed (Lazorenko et al., 2009). Results from an astrometric planet search around 20 M/L dwarfs over 2 yr suggests an accuracy of  $\sim 100 \mu\text{as}$  (Lazorenko et al., 2014).

Sahlmann et al. (2016) used VLT-FORS2 astrometry to observe the 4-planet system GJ 676A. With four relatively bright nearby stars, observations between 2010 April to 2012 August gave an average positional precision of  $0.43$  mas per epoch. This constrained the astromet-

ric reflex motion due to the  $P = 1052$ -d planet b, yielding  $i = 45_{-11}^{+21} (^\circ)$  and hence  $M_b = 6.7_{-1.5}^{+1.8} M_J$ , some 40% higher than the minimum mass,  $M_b \sin i$ , inferred from the radial velocity orbit.

Wertz et al. (2017) reported H-band images of the 4-planet system HR 8799 with VLT-SPHERE/IRDIS, yielding positions at epoch J2014.93 with an accuracy down to 2 mas, with associated orbital constraints.

### 3.2.2 Interferometry

For larger angular separations,  $\sim 0.5''$ , both theory (Lindgren, 1980, eqn 35b) and empirical data had shown that the turbulence-limited accuracy is  $\propto \theta^{1/3}$  and, to first order, is independent of telescope size. Given this dependency, long-baseline interferometry was therefore not immediately viewed as a technique that offered a significant advantage in relative positional accuracy for narrow-field measurements.

For two stars with an angular separation of  $0.5''$ , their light paths are separated by  $\sim 100$  m at the top of the turbulent atmosphere, at a height of  $\sim 10$  km. In conventional astrometry with long-focus telescopes, the telescope is much smaller than the beam separation, and the accuracy is independent of the telescope diameter.

However with interferometry, baselines can be larger than the beam separation, and a qualitative change in the behaviour of the atmospheric errors results.

Turbulence models applied to differential observations give the mean square error for an astrometric measurement, in arcsec (Shao & Colavita, 1992, eqn 2)

$$\sigma_{\delta}^2 \approx 5.25 B^{-4/3} \theta^2 \int h^2 C_n^2(h) (Vt)^{-1} dh, \quad (3.9)$$

where  $B$  is the baseline in m,  $\theta$  the star separation in arcmin,  $V(h)$  is the wind speed as a function of height, and  $t$  the integration time in sec.  $C_n^2(h)$  is a complicated function describing the vertical profile of the atmosphere's refractivity power spectrum, which drives atmospheric turbulence through temperature fluctuations. The equation applies in the very narrow-angle regime,  $\theta h \ll B$ , and for long integrations,  $t \gg B/V$ .

For the atmospheric conditions measured at Mauna Kea, Shao & Colavita (1992, eqn 4) found

$$\sigma_{\delta} \approx 300 B^{-2/3} \theta t^{-1/2} \text{ arcsec}. \quad (3.10)$$

The form is equivalent to the single aperture (Figure 3.5), with  $B$  replacing  $D$ , and the smaller numerical factor reflecting the (improved) site conditions at Mauna Kea.

Accordingly, interferometric accuracy depends linearly on star separation, and improves with increasing baseline. For  $\theta = 20$  arcsec,  $B = 200$  m, and  $t = 1$  h, this implies  $\sigma_{\delta} \approx 10 \mu\text{as}$  (Shao & Colavita, 1992). Vector formulation relevant for Earth-mass planet detection at sub- $\mu\text{as}$  levels is given by Savransky & Kasdin (2010).

**Antarctic** The integrated amplitude of  $C_n^2$  determines the seeing, usually quantified through the Fried parameter,  $r_0$ . At optical wavelengths, Antarctic seeing is typically  $\sim 1\text{--}3$  arcsec. But the determining factor for accurate interferometric astrometry is tilt anisoplanatism, viz. the second moment of the  $C_n^2$  profile in Equation 3.9 which, due to the  $h^2$  factor, is dominated by high-altitude turbulence. At the south pole, the  $C_n^2(h)$  profile is far less affected by phenomena (jet streams, trade winds, and high-altitude synoptic wind shear) that govern the behaviour at mid-latitudes (Marks et al., 1999).

Measurements from Dome C confirm long atmospheric coherence times, and large ( $\sim 30$  arcsec) isoplanatic angles over which the paths are temporally coherent (e.g. Lawrence et al., 2004; Kenyon et al., 2006; Kenyon & Storey, 2006). Lloyd et al. (2002) even reported seeing Jupiter scintillating, and their studies indicate that a 100 m interferometer at Dome C could achieve  $10 \mu\text{as}$  differential astrometry 300 times faster than a comparable interferometer at a good mid-latitude site.

### 3.3 Microarcsec astrometry

With the  $\mu\text{as}$  accuracy necessary for astrometric planet detection, a number of higher-order effects modify the apparent position of the target star. Their consideration is crucial for the global measurements by Gaia, although less so for differential measurements over small angles. Although their treatment is delicate, it should be possible to model their contributions accurately.

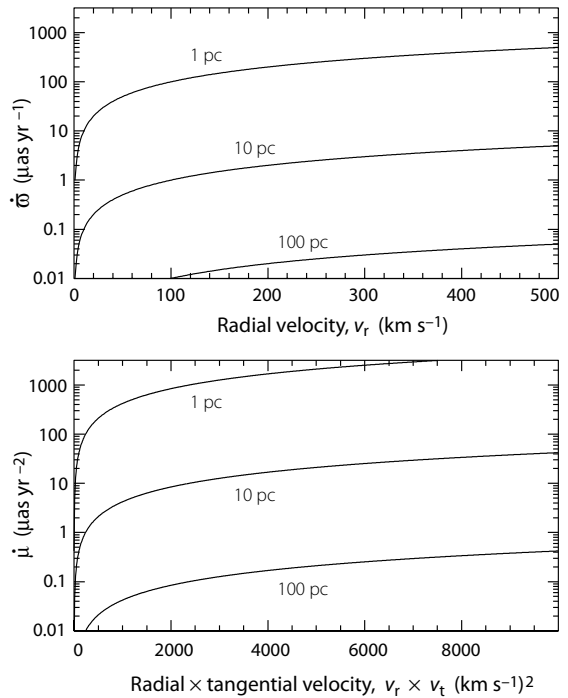


Figure 3.2: Effects of source motion on the parallax and proper motion (Equations 3.13–3.14) for three representative stellar distances. Top:  $\dot{\delta}$  as a function of radial velocity  $v_r$ ; and bottom:  $\dot{\mu}$  as a function of the product of the radial and tangential velocities,  $v_r \times v_t$ . Adapted from Sozzetti (2005, Figure 1).

#### 3.3.1 Light deflection

In terms of the angle  $\psi$  subtended at the observer between the Sun and a given star, the (post-Newtonian) light deflection angle due to the spherically symmetric part of the gravitational field of the Sun is (e.g. Will, 1993; Klioner, 2003, eqn 64)

$$\alpha_{\text{pN}} = \frac{(1 + \gamma)GM_{\odot}}{c^2 r_0} \cot \frac{\psi}{2}, \quad (3.11)$$

where  $G$  is the gravitational constant, and  $r_0$  is the distance between the observer and the Sun.  $\gamma$  is a variable in the *parameterised post-Newtonian* (ppN) formalism, with  $\gamma = 1$  in general relativity. With  $r_0 = 1$  au,  $\gamma = 1$ , and for a star at  $90^\circ$  to the ecliptic ( $\psi = 90^\circ$ ),  $\alpha_{\text{pN}} \approx 4$  mas. A star at  $\delta\psi = 1$  arcmin then experiences a differential light deflection  $\delta\alpha_{\text{pN}} \approx 1 \mu\text{as}$ .

Data analysis at the  $\mu\text{as}$  level for Gaia is formulated directly within the framework of general relativity, either using a non-perturbative approach (de Felice et al., 2004), or through the ppN formulation which is the present baseline (Klioner, 2003). Light deflection due to the solar quadrupole moment, and for observations near to Jupiter, are also included. In this framework, even the basic concepts of parallax, proper motion, and radial velocity have to be refined (Klioner, 2004, 2012).



### 3.3.2 Aberration

Displacement of an object's observed position resulting from the observer's motion with respect to the solar system barycentre is referred to as *aberration*. If  $\theta$  is the angle between the direction towards the source and the direction of the observer's velocity,  $v$ , then the angular shift  $\delta\theta$  toward the apex of the observer's motion is given by (Klioner, 2003, eqn 17)

$$\delta\theta = \frac{v}{c} \sin\theta \left[ 1 + \frac{1}{c^2} (1 + \gamma) w(x_0) + \frac{1}{4} \frac{v^2}{c^2} \right] - \frac{1}{4} \frac{v^2}{c^2} \sin 2\theta + \frac{1}{12} \frac{v^3}{c^3} \sin 3\theta + O(c^{-4}), \quad (3.12)$$

where  $\gamma$  is the ppN parameter, and  $w(x_0)$  is the gravitational potential of the solar system at the point of observation. For a satellite with barycentric velocity  $v \sim 40 \text{ km s}^{-1}$ , the first-order (classical) aberration is  $\sim 28 \text{ arcsec}$ , the second-order term may reach  $3.6 \text{ mas}$ , and third-order effects are  $\sim 1 \mu\text{as}$ . As a result of the size of the first-order term, an accuracy of  $1 \mu\text{as}$  furthermore requires that the observer's (barycentric coordinate) velocity should be known to  $\sim 10^{-3} \text{ m s}^{-1}$ .

### 3.3.3 Source motion

A star's velocity through space leads to a secular change in its observed proper motion  $\dot{\mu}$ , an effect referred to as *perspective acceleration*, while the radial component of its motion (its radial velocity) leads to a secular change in its trigonometric parallax  $\dot{\omega}$ . These can be written in the form (Dravins et al., 1999)

$$\dot{\mu} = -\frac{v_r}{A} 2\omega\mu \quad (3.13)$$

$$\dot{\omega} = -\frac{v_r}{A} \omega^2, \quad (3.14)$$

where  $A$  is the astronomical unit. In common units,  $\dot{\mu}$  and  $\dot{\omega}$  are in  $\text{arcsec yr}^{-2}$  and  $\text{arcsec yr}^{-1}$  respectively, if the radial velocity  $v_r$  is in  $\text{km s}^{-1}$ ,  $\omega$  is in  $\text{arcsec}$ ,  $\mu$  is in  $\text{arcsec yr}^{-1}$ , and the astronomical unit is expressed as  $A = 9.778 \times 10^5 \text{ arcsec km yr s}^{-1}$ .

Figure 3.2 shows  $\dot{\omega}$  as a function of  $v_r$ , and  $\dot{\mu}$  as a function of  $v_r \times v_t$ , where the tangential velocity  $v_t = 4.74\mu/\omega \text{ km s}^{-1}$  for  $\omega, \mu$  in  $\text{arcsec (yr}^{-1})$ . At  $\mu\text{as}$  accuracy levels, the effect of perspective acceleration remains significant out to tens of parsec for stars with large  $v_r$  and/or large  $v_t$ , while the secular change in parallax may be significant for nearby stars with large  $v_r$ .

### 3.3.4 Astrophysical limits

At  $\mu\text{as}$  astrometric accuracy, several astrophysical noise sources may contribute. Below  $1 \mu\text{as}$ , stellar surface structure (Eriksson & Lindgren, 2007), astrometric microlensing (Sazhin, 1996), and relativistic modeling

(e.g. Anglada-Escudé et al., 2007) may introduce significant barriers, while the effects of interstellar and interplanetary scintillation in the optical, and stochastic gravitational wave noise, will still be negligible (Perryman et al., 2001). Gravitational instabilities within circumstellar disks may produce detectable motion of the central star at the levels of  $10 - 100 \mu\text{as}$  on decade time scales at  $d = 100 \text{ pc}$  (Rice et al., 2003a). Effects of density waves on the motion of the disk's photocentre were considered by Takeuchi et al. (2005b).

**Stellar activity** Limits to the intrinsic accuracy of astrometric measurements may come from 'jitter' induced by stellar surface structure (star spots, plages, granulation, and non-radial oscillations) likely to produce fluctuations in the observed photocentre. Various detailed studies have been made (Bastian & Hefele, 2005; Reffert et al., 2005; Catanzarite et al., 2008; Lanza et al., 2008; Makarov et al., 2009; Cegla et al., 2013).

Svensson & Ludwig (2005) and Ludwig (2006) computed hydrodynamical model atmospheres for a range of stellar types, predicting both photometric and astrometric jitter caused by the effects of granulation, and finding that the latter is almost entirely determined by the surface gravity  $g$ , being proportional to  $g^{-1}$  for a wide range of models.

Eriksson & Lindgren (2007) constructed relatively well-defined statistical relations between variations in the photocentre, total flux, and radial velocity for a wide range of possible surface phenomena, and used the studies of surface structure carried out for radial velocity accuracy assessment (e.g. Saar & Donahue, 1997; Queloz et al., 2001; Henry et al., 2002; Saar et al., 2003; Hatzes, 2002; Paulson et al., 2004b) to predict the astrometric jitter in various star types, without detailed knowledge of their actual surface structures.

If the radial velocity variations are caused mainly by rotational modulation of the spotted surface, they find

$$\sigma_{\text{pos}} = \frac{R_\star \sigma_{v_R}}{v \sin i} \simeq 0.49 R_\star \sigma_m \quad (3.15)$$

$$\sigma_{v_R} \simeq 0.376 v \sin i \sigma_m \simeq 0.43 R_\star \left( \frac{2\pi}{P_{\text{rot}}} \right) \sigma_m \quad (3.16)$$

where  $\sigma_{\text{pos}}$ ,  $\sigma_{v_R}$  and  $\sigma_m$  are the rms scatter in astrometry, radial velocity, and magnitude,  $R_\star$  is the stellar radius,  $v \sin i$  the projected rotational velocity, and  $P_{\text{rot}}$  the stellar rotation period. The approximate forms were derived from Monte Carlo simulations.

For most stellar types, they predict that effects due to stellar surface structures will be of order  $\Delta \sim 10 \mu\text{as}$  or greater (or, equivalently,  $10/d \mu\text{as}$  where  $d$  is in pc). While this results in a negligible impact on the detection of large (Jupiter-size) planets, and on the determination of stellar parallax and proper motion, the effect exceeds the typical astrometric displacement caused by an Earth-size exoplanet in the habitable zone (§3.1). Only

**Reference systems and reference frames:** The 1991 IAU resolution on reference systems and reference frames (Wilkins, 1990) distinguishes between the two terms. A *reference system* is the complete specification of a celestial coordinate system, defining the origin and fundamental planes (or axes), and specifying the constants, models, and algorithms used to transform between observable quantities and reference data that conform to the system. A *reference frame* serves as the practical realisation of a reference system, consisting of a set of fiducial points on the sky (e.g. stars or quasars) along with their coordinates.

The fundamental plane of astronomical reference systems is conventionally taken to be the extension of the Earth's equatorial plane, at some date, to infinity. The declination of a celestial object is its angular distance north or south of this plane. The right ascension is its angular distance measured eastward along the equator from some agreed reference point, traditionally the equinox (the point at which the Sun crosses the equatorial plane moving from south to north). The Sun's apparent yearly motion lies in the ecliptic, the plane of the Earth's orbit. The equinox, therefore, is a direction in space along the nodal line defined by the intersection of the ecliptic and equatorial planes. Because neither of the planes are inertially fixed, but move slowly due to a combination of luni-solar and planetary precession, a reference system based on the equator and equinox must be associated with a specific date.

Star catalogues pre-1976 used the equator and equinox B1950. Based on the Besselian year (named after Friedrich Bessel), this depended on Newcomb's (1895) theory of the Earth's orbit. Earlier catalogues such as the Henry Draper Catalogue used B1900, while the IAU-adopted constellation boundaries of Delporte (1930) are defined relative to B1875.

In 1976, the IAU General Assembly adopted a new reference system based on the equator and equinox of J2000, determined from extensive observations of planetary motions, together with the IAU (1976) system of astronomical constants and related algorithms. The reference *frame* that embodied this system for practical purposes was the Fifth Fundamental Catalogue of 1535 stars (FK5, Fricke et al., 1988), and its 1991 extension of a further 3117 stars.

In 1997, the IAU General Assembly (Resolution B2) adopted the International Celestial Reference System (ICRS), with its origin at the solar system barycentre, and with kinematically non-rotating axes. The specifications include a metric tensor, a prescription for establishing and maintaining the axis directions, and algorithms for coordinate transformation (Johnston & de Vegt, 1999). The ICRS was itself materialised, with an accuracy of  $\pm 30 \mu\text{as}$ , by the International Celestial Reference Frame (ICRF), a positional catalogue of 608 extragalactic radio sources observed with VLBI, all strong ( $> 0.1 \text{ Jy}$ ) at wavelengths 13 and 3.6 cm (Ma et al., 1998). Most have faint optical counterparts (typically  $V > 18$ ) and the majority are quasars. Of these, 212 are defining sources that establish the orientation of the ICRS axes, which are themselves consistent with those of the J2000/FK5 system within the uncertainty of the latter (Arias et al., 1995; Folkner et al., 1994). The ICRF was updated to ICRF2 in 2009. ICRF2 is *defined* by the positions of 295 compact radio sources, and comprises 3414 sources measured using VLBI. It has a noise floor of  $\sim 40 \mu\text{as}$ , and an axis stability of  $\sim 10 \mu\text{as}$ .

IAU (1997) Resolution B2 also adopted the Hipparcos Catalogue as the primary realisation of the ICRS at *optical* wavelengths. This will soon be superseded by the Gaia Catalogue (Le Bail et al., 2016; Mignard et al., 2016).

Having established a reference *system*, the position of an object moving through space must be specified within that system at a particular *epoch*. Frequently, but not necessarily, the chosen epoch is J2000.0 (to be distinguished from the equinox 'labeling' of the obsolete IAU (1976) reference *system*). The Hipparcos and Tycho Catalogues, for example, have as their catalogue epoch  $T_0 = \text{J1991.25}(\text{TT})$ , a good approximation to the mean central epoch of the satellite observations. The inclusion of proper motions, along with the astrometric standard errors and their correlations, allows the Hipparcos star positions within the ICRS reference system to be calculated at any other epoch.

for stars with extremely low photometric variability ( $\leq 0.5 \text{ mmag}$ ) and low magnetic activity, comparable to that of the Sun, will the astrometric jitter be of order  $1 \mu\text{au}$ , sufficient for the astrometric detection of an Earth-sized planet in the habitable zone (Table 3.1).

The sun spot and plage properties of the Sun over one solar cycle have also been used to estimate detectability of an Earth-mass planet in the habitable zone at 10 pc using radial velocity and astrometry techniques (Lagrange et al., 2010b; Meunier et al., 2010a; Lagrange et al., 2011; Meunier & Lagrange, 2013a,b; Borgniet et al., 2015; Meunier et al., 2015). Compared to the astrometric signature of  $0.3 \mu\text{as}$ , the activity-induced signal along the equatorial plane has a typical amplitude  $\leq 0.2 \mu\text{as}$ .

## 3.4 Modeling planetary systems

### 3.4.1 Proper motion and parallax

In the absence of an orbiting companion there are five astrometric observables which describe a star's angular

position on the sky: the equatorial coordinates in right ascension and declination,  $\alpha_0, \delta_0$  (given at a specified epoch, typically J2000.0, and within a specified reference system, now conventionally the International Celestial Reference System ICRS; see box); the corresponding orthogonal components of proper motion  $\mu_{\alpha*}, \mu_{\delta}$  [with  $\mu_{\alpha*} = \mu_{\alpha} \cos \delta$  denoting an angle in great-circle measure]; and the parallax  $\varpi$  [a designation often adopted in preference to  $\pi$  to avoid confusion with the mathematical constant]. An orbiting planet results in further perturbation of these observables, detailed below.

### 3.4.2 Multiple planets

The dynamical effect of multiple planets contributes to the total astrometric signature in the same way as the Sun's path over decades reflects the combined gravitational effects of all solar system objects (Figure 3.3a). As noted in the first discussions of the Sun's orbital revolution about the solar system barycentre by Newton (as quoted by Cajori, 1934) the actual motion of the Sun is

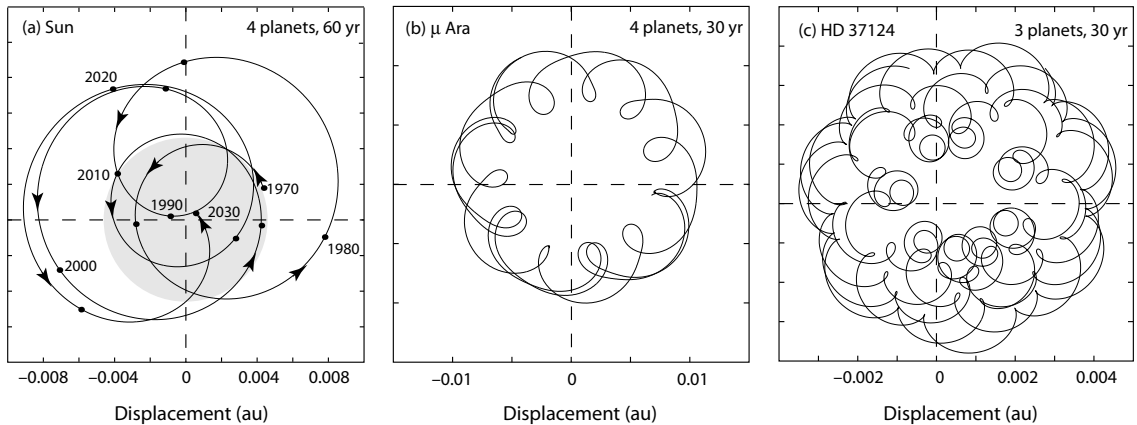


Figure 3.3: Multi-planet host star motions with respect to their system barycentre. (a) Path in the ecliptic plane of the Sun's reflex motion about the solar system barycentre, 1970–2030, due to the four giant planets. The scale of the displacement is indicated by the grey circle which shows the solar diameter ( $R_{\odot} = 6.96 \times 10^8$  m, or  $0.00465$  au) positioned at the barycentre. Close approaches between Sun and barycentre, or 'peribacs' (Fairbridge & Shirley, 1987), recur at mean intervals of 19.86 yr. Around 1990 (solid circle near centre) the Sun had a retrograde motion relative to the barycentre. (b–c) Barycentric motions of the multiple exoplanet host stars  $\mu$  Ara and HD 37124 over the 30-year interval 2000–2030. From Perryman & Schulze-Hartung (2011, Figure 2).

rather complex 'since that centre of gravity is continually at rest, the Sun, according to the various positions of the planets, must continuously move every way, but will never recede far from that centre.'

Perryman & Schulze-Hartung (2011) determined the barycentric motion of the host stars of known multiple exoplanet systems. Examples of the complex star paths in their orbit plane that result from the linear superposition of the reflex motions due to the Keplerian orbit of each individual planet around that star–planet barycentre (Equation 3.1) are shown in Figure 3.3(b–c).

A curve similar to the symmetric part of Figure 3.3b, illustrating the orbit of Mars viewed from Earth, appeared in Kepler's 1609 *Astronomia Nova*. These families of curves have been named *planet mandalas*, after the Sanskrit for circle (Wolfram, 2010). A suggested relation between the Sun's barycentric motion and solar activity is detailed in Section 12.1.6.

### 3.4.3 Keplerian elements

A planetary orbit determined astrometrically is characterised by the seven Keplerian parameters (§2.1.1):  $a, e, t_p, i, \Omega, \omega, P$  (observations of the semi-major axis in angular measure,  $a''$ , can be converted into linear measure using the star distance). A system with  $n_p$  planets therefore requires a total of  $5 + 7 \times n_p$  parameters.

In a simplistic picture, as for orbit reconstruction in the case of radial velocity observations, each planet would have its own orbital frequency, and Fourier analysis of the total signal would reveal the various planets. In practice, a planet in an eccentric orbit might have harmonics which could be interpreted as distinct planets,

while a long-period planet observed over a short time might have noise generated at many frequencies due to the difficulty of distinguishing an orbital arc from the star's proper motion.

Numerous studies have investigated the sensitivity of astrometric measurements for the detection of exoplanets and for the measurement of their orbital elements and masses (e.g. Black & Scargle, 1982; Eisner & Kulkarni, 2001a, 2002; Konacki et al., 2002; Pourbaix, 2002; Sozzetti, 2005).

**Orbit fitting** For multiple planet systems detectable by Gaia and (the no-longer considered) SIM, studies of the fitting procedures have shown them, as in the case of radial velocity modeling for multiple systems, to be highly non-linear (Casertano et al., 2008; Wright & Howard, 2009; Traub et al., 2010). Studies of the astrometric detection of multiple planets in mean motion resonance, in the context of the proposed Chinese STEP mission, have been detailed by (Wu et al., 2016a).

Given this complexity, various algorithms for single- and multiple-component orbital fits are being developed for use with the Gaia and SIM-type data (alone or together with radial velocity data), either based on frequency decomposition (Konacki et al., 2002), using minimisation techniques to optimally search the orbital parameter space, such as Levenberg–Marquardt or Markov Chain Monte Carlo analysis (Ford & Gregory, 2007), or using partial linearisation.

If the planet's orbital period is close to one year, and if its orbital plane is nearly parallel to the ecliptic, reflex motion of the host star may be entirely or partially absorbed by the Earth's orbital motion (Butkevich, 2017).

### 3.4.4 Mass and orbit inclination

Unlike radial velocity (Doppler shift) measurements, which have an intrinsic  $M_p \sin i$  degeneracy since the orbit inclination,  $i$ , is undetermined, astrometric measurements provide  $a$  and  $i$  separately. With  $M_\star$  estimated from its spectral type or evolutionary models, then the astrometric displacement yields  $M_p$  directly.

For multiple planet systems, astrometry can also (in principle) determine the relative inclinations between pairs of orbits (van de Kamp, 1981, eqn 16.5)

$$\cos \Delta i = \cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos(\Omega_1 - \Omega_2). \quad (3.17)$$

One objective of such studies is to establish the occurrence of co-planar orbits, an important ingredient for formation theories and dynamical stability analyses.

### 3.4.5 Planet–planet interactions

In numerous multi-planet systems, e.g. GJ 876 (Bean & Seifahrt, 2009), gravitational planet–planet interactions will significantly alter the radial velocity and/or astrometric signature of the system, and a full dynamical fit involving an N-body code may be needed to ensure the short- and long-term stability of the solution.

**Linearisation** The four elements  $a, \omega, i, \Omega$  can be replaced by the Thiele–Innes constants (Thiele, 1883; Binnendijk, 1960; Heintz, 1978a) which are better suited to orbital description in rectangular coordinates

$$\begin{aligned} A &= a(+\cos \omega \cos \Omega - \sin \omega \sin \Omega \cos i) \\ B &= a(+\cos \omega \sin \Omega + \sin \omega \cos \Omega \cos i) \\ C &= a \sin \omega \sin i \\ F &= a(-\sin \omega \cos \Omega - \cos \omega \sin \Omega \cos i) \\ G &= a(-\sin \omega \sin \Omega + \cos \omega \cos \Omega \cos i) \\ H &= a \cos \omega \sin i. \end{aligned} \quad (3.18)$$

These are related to the direction cosines of the major and minor axes of the orbit in the  $xy$  tangent plane,  $(A/a, B/a, C/a)$ ,  $(F/a, G/a, H/a)$ . Analogous constants appeared in Gauss' treatment of planetary orbits.

Tangential coordinates in the plane of the sky (cf. Figure 2.2) are then given by (Heintz 1978a, eqn 15–16; van de Kamp 1981, eqn 10.6)

$$\begin{aligned} x &= AX + FY \\ y &= BX + GY, \end{aligned} \quad (3.19)$$

$$z = r \sin i \sin(\omega + \nu) = CX + HY, \quad (3.20)$$

where  $XY$  are elliptical rectangular coordinates in the orbit plane defined as

$$\begin{aligned} X &= \cos E(t) - e \\ Y &= \sqrt{1 - e^2} \sin E(t), \end{aligned} \quad (3.21)$$

and  $E(t)$  is the eccentric anomaly.

The astrometric displacement of a star in equatorial coordinates, at time  $t$ , due to parallax, proper motion, and a system of  $n_p$  unseen planets is then generalised as (Wright & Howard, 2009, eqn 49–50)

$$\begin{aligned} \Delta \alpha(t) \cos \delta &= \sum_{j=1}^{n_p} [B_j X_{j,t} + G_j Y_{j,t}] + \\ &\Delta \alpha_0 \cos \delta + \varpi \Pi_{\alpha,t} + \mu_\alpha(t - t_0) \end{aligned} \quad (3.22)$$

$$\begin{aligned} \Delta \delta(t) &= \sum_{j=1}^{n_p} [A_j X_{j,t} + F_j Y_{j,t}] + \\ &\Delta \delta_0 + \varpi \Pi_{\delta,t} + \mu_\delta(t - t_0), \end{aligned} \quad (3.23)$$

where  $(\Delta \alpha_0 \cos \delta, \Delta \delta_0)$  accounts for an adjustment to the nominal star position, and  $(\Pi_{\alpha,t}, \Pi_{\delta,t})$  are the orthogonal components of the displacements due to parallax (Green, 1985; Seidelmann, 1992)

$$\Pi_{\alpha,t} = r_x(t) \sin \alpha - r_y(t) \cos \alpha$$

$$\Pi_{\delta,t} = [r_x(t) \cos \alpha + r_y(t) \sin \alpha] \sin \delta - r_z(t) \cos \delta. \quad (3.24)$$

$(r_x, r_y, r_z)$  are the Cartesian components of the observer position with respect to the solar system barycentre.

**Combining astrometry and radial velocities** Four orbital elements are in common between astrometric and spectroscopic solutions:  $a, e, \omega, t_p$ . Combined observations therefore further constrain the three-dimensional orbit, and can yield individual component masses without the ambiguity of the orbital inclination.

The approach used for the combination of HST-FGS astrometry and radial velocity orbits is described in detail by Benedict et al. (2002). This proceeds by first constraining all 'plate constants' (image scale, rotation, offsets, radial terms, and parallax factors) to those determined from their astrometry-only solution. They then determine the orbital elements  $K, e, P, \omega$  from the available radial velocity data.

Their final step is to fully constrain the orbit by minimising the astrometric and radial velocity residuals according to the identity given by Equation 2.23 (as proposed by Pourbaix & Jorissen, 2000, their eqn 12)

$$\frac{a'' \sin i}{\varpi} = \frac{PK\sqrt{1 - e^2}}{2\pi}. \quad (3.25)$$

Here, the left-hand side contains quantities derived only from the astrometric solution (parallax  $\varpi$ , angular semi-major axis  $a''$ , and orbital inclination  $i$ ), and the right-hand side are those from the radial velocity orbit (period  $P$ , radial velocity semi-amplitude of the visible component  $K$ , and eccentricity  $e$ ).

Further considerations of the linear formulation of the combined astrometric and radial velocity solution is given by Wright & Howard (2009).

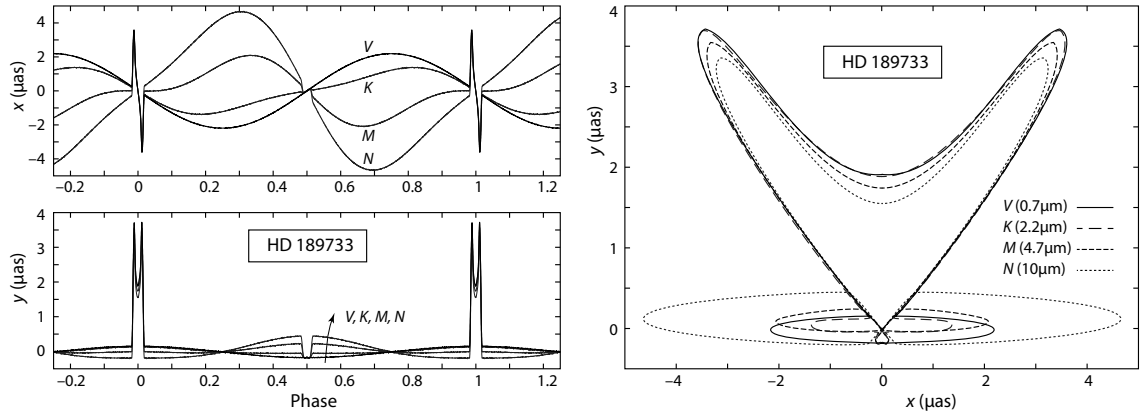


Figure 3.4: Predicted wavelength-dependent astrometric orbit for HD 189733. Left:  $x$  and  $y$  components of motion versus phase. Right: sky-projected orbit. The origin is the system barycentre, and the projected orbital rotation axis is parallel to  $y$ . Phase 0 is the primary transit, phase 0.5 is the secondary eclipse. The out-of-transit/eclipse signature deviates from a sinusoid due to the day/night temperature difference. From Coughlin & López-Morales (2012b, Figure 6), by permission of IOP Publishing/AAS.

### 3.4.6 Wavelength dependence

Most astrometric considerations assume that the star-planet photocentre is dominated by the stellar light, and with this photocentre orbiting the barycentre.

However, contributions from the planet's thermal and/or reflected emission cause the photocentre to shift towards the planet with increasing wavelength as a result of its lower  $T_{\text{eff}}$  (Coughlin & López-Morales, 2012b, eqn 10). The astrometric signature becomes

$$\alpha = \left( \frac{q-l}{(1+q)(1+l)} \right) \left( \frac{a}{1 \text{ au}} \right) \left( \frac{d}{1 \text{ pc}} \right)^{-1} \text{ arcsec}, \quad (3.26)$$

where the mass and luminosity ratios are  $q = M_p/M_\star$ ,  $l = L_p/L_\star$ . This reduces to Equation 3.1 for  $l \rightarrow 0$ .

Observed at long enough (and at multiple) wavelengths, the planet may dominate the astrometric motion (with negative  $\alpha$ ), and it should be feasible to measure both planet and star orbits separately, and thus their individual masses.

Coughlin & López-Morales (2012b) predict some of the largest displacements (at a few  $\mu\text{as}$ ) for the transiting systems WASP-12, HD 209458, and HD 189733, as well as the Neptune-mass planets, 55 Cnc e, GJ 436 b, and GJ 1214 b. This shows that the effect can be relatively prominent for large low-mass planets orbiting large high-mass stars, a parameter space not well covered by other techniques. Transiting exoplanets would allow determination of the radii of the planet and star via astrometry alone. Planet albedos and day-night contrast ratios further affect the photocentric motion.

Coughlin & López-Morales (2012b) give predicted wavelength-dependent astrometric orbits for WASP-12, HD 209458, and HD 189733 (Figure 3.4), showing some of these effects. The required sub- $\mu\text{as}$  accuracies at  $\lambda = 2 - 10 \mu\text{m}$ , however, present an observational challenge unlikely to be met in the immediate future.

### 3.4.7 Coordinate transformations

**Galactic coordinates** The Hipparcos and Tycho catalogues, in common with other astrometric catalogues, provide positions and proper motions within the *equatorial system* (box, page 86). Various studies of the host stars make use of Galactic coordinates, or space velocities derived from proper motions and radial velocities. The two relevant transformations are given hereafter (Perryman et al., 1997b, Volume 1, Section 1).

The basis vectors in the equatorial system are denoted  $[\mathbf{x} \mathbf{y} \mathbf{z}]$ , with  $\mathbf{x}$  being the unit vector towards  $(\alpha, \delta) = (0, 0)$ ,  $\mathbf{y}$  the unit vector towards  $(\alpha, \delta) = (+90^\circ, 0)$ , and  $\mathbf{z}$  the unit vector towards  $\delta = +90^\circ$ . Denoting the basis vectors in Galactic coordinates as  $[\mathbf{x}_G \mathbf{y}_G \mathbf{z}_G]$ , an arbitrary direction  $\mathbf{u}$  may be written in terms of equatorial or Galactic coordinates as

$$\mathbf{u} = [\mathbf{x} \mathbf{y} \mathbf{z}] \begin{pmatrix} \cos \delta \cos \alpha \\ \cos \delta \sin \alpha \\ \sin \delta \end{pmatrix} = [\mathbf{x}_G \mathbf{y}_G \mathbf{z}_G] \begin{pmatrix} \cos b \cos l \\ \cos b \sin l \\ \sin b \end{pmatrix}. \quad (3.27)$$

The transformation between them is given by

$$[\mathbf{x}_G \mathbf{y}_G \mathbf{z}_G] = [\mathbf{x} \mathbf{y} \mathbf{z}] \mathbf{A}_G, \quad (3.28)$$

where the matrix  $\mathbf{A}_G$  relates to the definition of the Galactic pole and centre in the International Celestial Reference System (ICRS, page 86). In the published Hipparcos catalogue, the following definitions in the ICRS were adopted for the north Galactic pole  $(\alpha_G, \delta_G)$ , and for the origin of Galactic longitude defined by the longitude of the ascending node of the Galactic plane on the equator of ICRS,  $l_\Omega$

$$\alpha_G = 192^\circ 85948, \quad (3.29)$$

$$\delta_G = +27^\circ 12825, \quad (3.30)$$

$$l_\Omega = 32^\circ 93192. \quad (3.31)$$

The angles  $\alpha_G$ ,  $\delta_G$  and  $l_\Omega$ , considered as exact quantities, are consistent with the previous (1960) definition of Galactic coordinates to a level set by the quality of optical reference frames prior to Hipparcos. The transformation matrix  $A_G$  may be computed to any desired accuracy; to 10 decimal places the result is

$$\mathbf{A}_G = \begin{pmatrix} -0.0548755604 & +0.4941094279 & -0.8676661490 \\ -0.8734370902 & -0.4448296300 & -0.1980763734 \\ -0.4838350155 & +0.7469822445 & +0.4559837762 \end{pmatrix}. \quad (3.32)$$

The star's Galactic longitude and latitude can then be computed from

$$\begin{pmatrix} \cos b \cos l \\ \cos b \sin l \\ \sin b \end{pmatrix} = \mathbf{A}'_G \begin{pmatrix} \cos \delta \cos \alpha \\ \cos \delta \sin \alpha \\ \sin \delta \end{pmatrix}. \quad (3.33)$$

**Space coordinates and velocity** The position of a star with respect to the solar system barycentre,  $\mathbf{b}$ , measured in pc, and its barycentric space velocity,  $\mathbf{v}$ , measured in  $\text{km s}^{-1}$ , are given in equatorial components by

$$\begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix} = \mathbf{R} \begin{pmatrix} 0 \\ 0 \\ A_p / \omega \end{pmatrix}, \quad (3.34)$$

$$\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = \mathbf{R} \begin{pmatrix} k\mu_{\alpha*} A_p / \omega \\ k\mu_{\delta} A_p / \omega \\ k v_r \end{pmatrix}, \quad (3.35)$$

with  $\mu_{\alpha*} = \mu_{\alpha} \cos \delta$ , and

$$\mathbf{R} = \begin{pmatrix} -\sin \alpha & -\sin \delta \cos \alpha & \cos \delta \cos \alpha \\ \cos \alpha & -\sin \delta \sin \alpha & \cos \delta \sin \alpha \\ 0 & \cos \delta & \sin \delta \end{pmatrix}. \quad (3.36)$$

$A_p = 1000 \text{ mas pc}$  and  $A_p = 4.74047\dots \text{ km yr s}^{-1}$  designate the astronomical unit in appropriate units,  $v_r$  is the radial velocity, and  $k = (1 - v_r/c)^{-1}$  is the Doppler factor. Galactic components of  $\mathbf{b}$  and  $\mathbf{v}$  can be obtained through pre-multiplication by  $\mathbf{A}'_G$ , as in Equation 3.33.

The components of space velocity in the Galactic coordinate system are usually designated  $U$ ,  $V$ , and  $W$ , with  $U$  positive in the direction of the Galactic centre,  $V$  positive in the direction of Galactic rotation, and  $W$  positive in the direction of the North Galactic Pole.

**Transformation between epochs** A more detailed problem is the transformation of stellar positions, parallaxes, proper motions, and radial velocities from one epoch to another. Butkevich & Lindgren (2014) provide rigorous and explicit formulae, including the Jacobian matrix (for a full error propagation), assuming uniform rectilinear motion and taking light-time effects into account. Light-time effects are generally very small, but exceed  $0.1 \text{ mas}$  or  $0.1 \text{ m s}^{-1}$  over  $100 \text{ yr}$  for at least 33

Hipparcos stars. For high-velocity stars within a few tens of pc from the Sun, light-time effects are generally more important than the effects of the curvature of their orbits in the Galactic potential. The effects will be more critical in the case of the Gaia Catalogue.

### 3.5 Astrometric searches from the ground

Narrow-field astrometry using large aperture telescopes at the sub-mas level, and using interferometers with adaptive optics at Keck-I and VLTI at the  $10 - 100 \mu\text{as}$  level, has led to various astrometric planet search programmes from the ground. There is an extensive literature on the search for, and constraints on, substellar or brown dwarf companions (see, e.g., Sahlmann et al., 2013b). Imaging observations to identify or confirm co-moving companions are discussed further in Chapter 7.

#### 3.5.1 Single mirror

**Palomar: STEPS** Accuracy limits measured at the 5-m Palomar telescope (Pravdo & Shaklan, 1996) motivated the STEllar Planet Survey (STEPS), an astrometric survey for giant planet and brown dwarf companions around some 30 nearby M-dwarfs (Pravdo et al., 2005; Pravdo & Shaklan, 2009a). The survey has detected several brown dwarf companions over its 10-year programme.

Their first proposed planet mass detection around the nearby (6 pc) low-mass ( $0.08 M_{\odot}$ ) cool M8 V star, VB 10, was reported by Pravdo & Shaklan (2009b), the most recent of the claimed astrometric discoveries (see box on page 83). From a simultaneous fit of the astrometry and low-precision radial velocity data, they derived  $M_p \sim 6.4 M_J$ ,  $P = 0.744 \text{ yr}$ ,  $a = 0.36 \text{ au}$  (62 mas),  $i = 96^\circ 9$ , and a resulting astrometric signature  $\alpha \sim 5 \text{ mas}$ . The existence of the planet was weakly supported by  $300 \text{ m s}^{-1}$  precision near-infrared radial velocities from Keck II-NIRSPEC (Zapatero Osorio et al., 2009), but ruled out using  $10 \text{ m s}^{-1}$  near-infrared measurements from VLT-CRIRES (Bean et al., 2010c), and probably from independent  $200 \text{ m s}^{-1}$  accuracy data (Anglada-Escudé et al., 2010b), as well as  $0.1 \text{ mas}$  astrometry from VLT-FORS2 (Lazorenko et al., 2011).

**Las Campanas: CAPS** The Carnegie Astrometric Planet Search started in 2007 using the 2.5-m du Pont telescope at Las Campanas, Chile (Boss et al., 2009). It follows about 100 very nearby ( $\leq 10 \text{ pc}$ ) stars, principally late M, L, and T dwarfs (generally too faint and/or red for Doppler surveys), for 10 yr. The astrometric accuracy, of about  $0.3 \text{ mas}$  per measurement epoch, is sufficient to detect a  $1 M_J$  planet at 1 au from a late M dwarf at 10 pc. The expected astrometric signature for the nearby M dwarf GJ 317 lies just below the current detectability limits (Anglada-Escudé et al., 2012b).

**VLT-FORS2** An astrometric planet search around 20 M/L transition dwarfs over two years has suggested an accuracy of  $\sim 100 \mu\text{as}$  over that interval (Sahlmann

et al., 2014; Lazorenko et al., 2014). Astrometric monitoring at the mas-level of the two-component brown dwarf system WISE J1049–53 established the orbital motion and parallax ( $d = 2.020 \pm 0.019$  pc), along with perturbations suggesting the presence of a substellar companion (Boffin et al., 2014).

**MEarth** The MEarth survey is a transit-based search for small rocky planets around the smallest, nearest stars to the Sun (§6.4.3). Potential M dwarf target stars are selected by their high proper motion combined with their red colours. An astrometric survey of 1507 mid-to-late M dwarfs gave parallaxes of  $\sim 5$  mas precision (Dittmann et al., 2014). The MEarth sample is mostly complete to 20–25 pc depending on spectral type, with 8 stars within 10 pc obtaining new parallax estimates.

**CTIO–SMARTS/RECONS** The CTIO/SMARTS 0.9-m telescope has also provided a number of M dwarf parallaxes from observations over 3–13 years as part of the RECONS long-term astrometry and photometry programme (Lurie et al., 2014).

### 3.5.2 Discoveries and candidates

At the end of 2017, the NASA Exoplanet Archive lists just one object as an astrometric discovery: DE 0823–49 b (DENIS–P J082303.1–491201 b). Discovered from VLTI–FORST2 astrometry, it is a brown dwarf ( $28.5 M_J$ ,  $e = 0.345$ ,  $P = 246$  d) orbiting a  $0.75 M_\odot$  L1.5 dwarf at 20 pc (Sahlmann et al., 2013b,c).

The Extrasolar Planets Encyclopaedia also lists one (different) discovery: HD 176051 b ( $1.5 M_J$ ,  $P = 1016$  d), a circumprimary planet at 15 pc discovered with Palomar–PHASES (Muterspaugh et al., 2010b). The authors comment that *‘as the latest in a long history of claimed astrometric planet detections, for which all previous claims have been demonstrated to be false, these may represent either the first such companions detected, or the latest in the tragic history of this challenging approach.’*

A  $P = 6.3$ -yr substellar companion around Sirius (Benest & Duvent, 1995), was not confirmed by deep imaging (Thalmann et al., 2011). Around 51 Peg, three common proper motion companions noted by Greaves (2006) are unlikely to be bound (Mamajek, 2010).

### 3.5.3 Optical interferometry

**Palomar PTI: PHASES** The Palomar Testbed Interferometer is a near-infrared instrument, with maximum baseline 100 m, which ceased normal operations in 2008. PHASES (Palomar High-precision Astrometric Search for Exoplanet Systems, Muterspaugh et al., 2010c), used phase-referenced imaging to achieve  $\sim 100 \mu\text{as}$  accuracy for  $\sim 30$ -arcsec binaries (Lane et al., 2000) and  $20 - 50 \mu\text{as}$  for sub-arcsec binaries (Lane & Muterspaugh, 2004). Observations of 51 sub-arcsec binaries excluded tertiaries of a few  $M_J$  with  $a < 2$  au in several systems (Muterspaugh et al., 2006, 2010a), with some substellar candidates needing confirmation (Muterspaugh et al., 2010b).

**VLTI–PRIMA: ESPRI** ESO’s VLTI (Very Large Telescope Interferometer) comprises four fixed 8.2 m Unit Telescopes, four moveable 1.8-m Auxiliary Telescopes, and six delay lines for baselines up to 200 m at  $1 - 13 \mu\text{m}$ . PRIMA (Phase-Referenced Imaging and Microarcsecond Astrometry) envisaged dual-feed for (initially) two UTs or ATs, for interferometric observations of two objects separated by  $\leq 1$  arcmin. It targeted  $10 - 50 \mu\text{as}$  accuracies in its narrow-field differential mode (Delplancke, 2008; Launhardt et al., 2008; Launhardt, 2009; Schmid et al., 2012; Sahlmann et al., 2012).

The ESPRI consortium (Exoplanet Search with PRIMA, Launhardt et al., 2008; Quirrenbach et al., 2011b; Sahlmann et al., 2013a) targeted a 5-yr survey of low-mass planets around stars within 15 pc, planets orbiting young stars ( $5 - 300$  Myr) within 100 pc, and known radial velocity planets within 200 pc. The initial target list of  $\sim 900$  stars was further restricted by the availability of suitable reference stars (Beust et al., 2011) to  $\sim 100$  priority candidates. With early on-sky performance more than an order of magnitude less performant than targeted, PRIMA was cancelled by ESO in 2014 February.

**VLTI–GRAVITY** GRAVITY is a second-generation VLTI instrument for high-precision narrow-angle astrometry and phase-referenced interferometric imaging in the K-band ( $2.2 \mu\text{m}$ ), targeting  $10 \mu\text{as}$  astrometry over the VLTI 2 arcsec field (Eisenhauer et al., 2011; Blind et al., 2015). It combines light from four Unit Telescopes or Auxiliary Telescopes, measuring the interferograms from six baselines simultaneously. The instrument has three main components: the infrared wavefront sensors, the beam combiner, and a laser metrology system (e.g. Anugu et al., 2018). Scientific goals focus on the dynamics associated with the black hole at the Galactic centre, but they also include the potential to detect a  $3 M_\oplus$  planet around an M5V star at 5 pc. Commissioning started in 2016 (Abuter et al., 2017), and by early 2018 a number of scientific results (unrelated to exoplanets) have been published.

**Keck: ASTRA** The Keck interferometer combined light from the two 10-m diameter primary mirrors, separated by 85 m, for near-infrared fringe visibility and mid-infrared nulling observations (Keck–I, Ragland et al., 2008). The ASTRA (ASTrometric and phase-Referenced Astronomy) upgrade (Pott et al., 2009; Woillez et al., 2010) targeted dual-star capability to carry out narrow-angle astrometry at the  $100 \mu\text{as}$  level between pairs of objects separated by  $\leq 20 - 30$  arcsec. The Keck interferometer project was terminated in 2012.

## 3.6 Astrometry from space: principles

Above the Earth’s atmosphere, the theoretical accuracies given by Equation 3.4 are essentially achievable, given the appropriate control and calibration of instrumental terms, such as attitude jitter and time-varying optical distortions (e.g., due to thermal effects).

There are two fundamentally different measurement approaches employed in practice. The first, as used on ground, and as exemplified by the Fine Guidance System on the Hubble Space Telescope in space (§3.7), is to make differential measurements over a small field of view. Short-term single measurement astrometric precision at the 1 mas-level is also reported for the Kepler mission, and has been exploited in studies of ‘variability induced motion’ detailed further in Section 6.14.13.

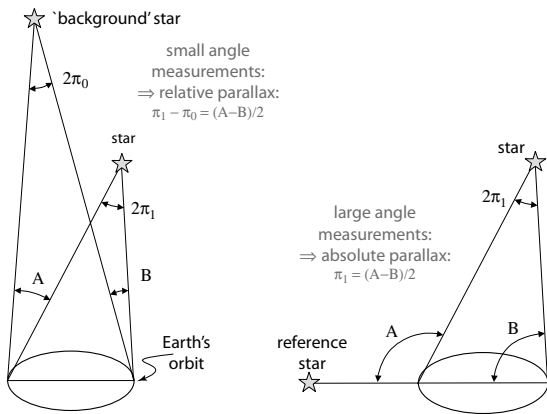


Figure 3.5: Principles of wide-field astrometric measurements from space, used by Hipparcos and Gaia. In traditional narrow-field astrometry (left), the parallax of the target star is only measured relative to the (strictly) unknown parallax of the reference star(s). Large angle measurements, with two superimposed fields (right), provides the basis for the determination of absolute parallax measurements. Courtesy Lennart Lindegren.

The second, pioneered by Hipparcos and substantially advanced by Gaia, is to adopt two widely-separated viewing directions, and a uniform ‘revolving scanning’ of the celestial sphere, to create an all-sky catalogue of star positions, proper motions, and parallaxes. The concept was proposed in outline by Pierre Lacroute in 1968, and advanced by Erik Hog, Lennart Lindegren, and others. Crucially, the wide-field concept allows for the provision of *absolute* trigonometric parallaxes, rather than the relative parallaxes accessible to narrow-field astrometry, whether from the ground or space (Figure 3.5).

Observations are reduced to an internally consistent and ‘rigid’ catalogue of positions and proper motions, but whose system orientation and angular rate of change are essentially arbitrary, since the measured arc lengths between objects are invariant to frame rotation. Placing both positions and proper motions on an inertial system corresponds to determining these 6 degrees of freedom (3 orientation and 3 spin components). For Hipparcos, they were derived using a combination of indirect differential measurements at optical and radio wavelengths (Kovalevsky et al., 1997). For Gaia, they will be derived directly using the large numbers of observed quasars (Claeskens et al., 2006; Perryman et al., 2014b).

In all cases, the objective is to detect the gravitational displacement of the host star due to any orbiting planet(s), quantified by the residuals from the reference model of the star’s rectilinear space motion.

### 3.7 Astrometry from space: HST

HST’s Fine Guidance Sensors allow for narrow-angle relative astrometry (Benedict et al., 1999, 2000). Within the

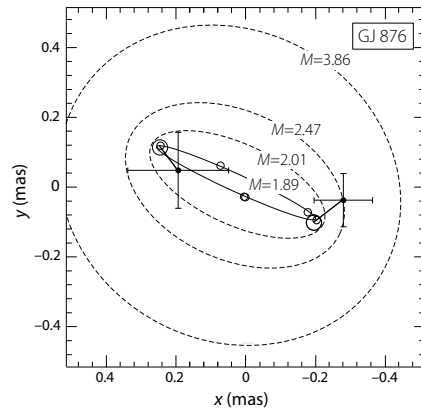


Figure 3.6: HST-FGS astrometry of GJ 876, showing four possible primary star orbits due to the perturbation by the longest period planet GJ 876 b, labeled according to inferred mass ( $M_J$ ). The densest sets of observations, at pericentre and apocentre, are shown by large circles. The astrometry-only residual normal points at phases 0.26 (pericentre, lower right) and 0.72 are shown as large crosses, connected to the derived orbit by their residual vectors. From Benedict et al. (2002, Figure 3), by permission of IOP Publishing/AAS.

field (the FGS pickle), the single-measurement precision at  $V \leq 16$  mag is 1–2 mas, primarily limited by residual spacecraft jitter. From multiple measurements, astrometric signatures down to  $\sim 0.25$  mas can be detected (McArthur et al., 2010, section 4.2). Astrometric results include a number of constraints on exoplanet candidates (Benedict et al., 2017).

*55 Cnc*: McGrath et al. (2002) gave an upper mass limit for the first planet in the 55 Cnc system, 55 Cnc b, of  $\sim 30M_J$ . McArthur et al. (2004) determined  $M_p = 17.7 \pm 5M_\oplus$  for the inner planet, 55 Cnc e, under the assumption of co-planarity.

*GJ 876*: Benedict et al. (2002) measured an astrometric signature  $\alpha = 0.25 \pm 0.06$  mas for GJ 876 b, from a combined fit to HST-FGS astrometry and high-precision radial velocities (Figure 3.6). Assuming  $M_\star = 0.32M_\odot$ , they determined a preferred solution  $M_p = 1.89 \pm 0.34M_J$ ,  $i = 84 \pm 6^\circ$ ,  $\alpha = 0.25 \pm 0.06$  mas, and  $\omega = 214.6 \pm 0.2$  mas.

Bean & Seifahrt (2009) constrained the co-planarity of planets b and c using a combination of Doppler measurements, HST-FGS astrometry, and dynamical considerations. They determined a mutual inclination  $\Delta i_{bc} = 5.0_{-2.3}^{+3.9}$  degrees, concluding that the planets probably formed in a circumstellar disk, and that their subsequent dynamical evolution into a 2:1 mean motion resonance only led to excitation of a small mutual inclination.

*$\epsilon$  Eri*: Benedict et al. (2006) measured an astrometric displacement due the long-period planet in  $\epsilon$  Eri of  $\alpha = 1.88 \pm 0.20$  mas, and a resulting mass  $M_p = 1.55 \pm 0.24M_J$ . A similar solution was found from the Hipparcos residuals (Reffert & Quirrenbach, 2011).



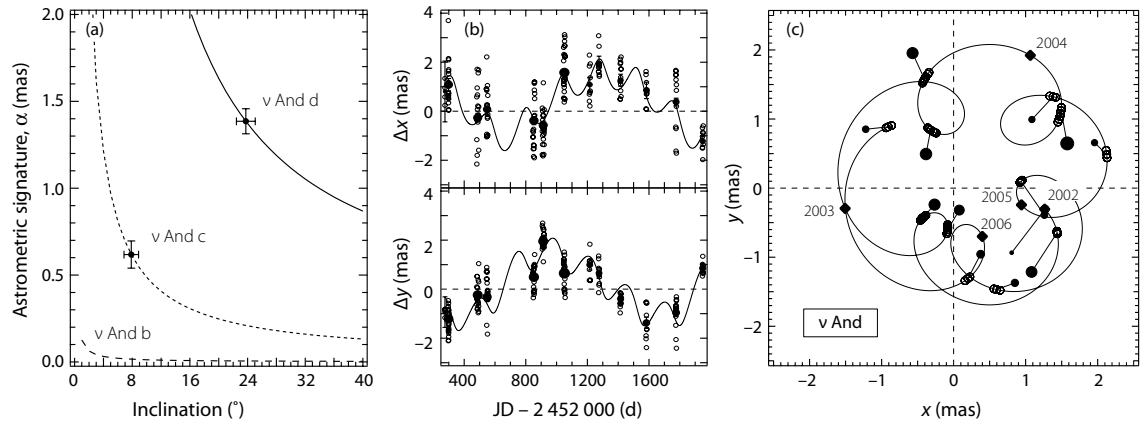


Figure 3.7: *v And* observed with HST-FGS: (a) astrometric signature versus orbit inclination, with the HST-FGS determinations for planets c and d indicated; (b) components of the stellar reflex motion due to planets b and c. Filled circles indicate normal points, with size proportional to the number of measurements at that epoch (open circles); (c) astrometric reflex motion of *v And* due to planets c and d. The solid curve shows the modeled motion (cf. Figure 3.3). Open circles show times of observations, and filled circles indicate associated normal points. From McArthur et al. (2010, Figures 7, 9, 10), by permission of IOP Publishing/AAS.

*v And*: The results for *v And* (McArthur et al., 2010) illuminate the prospects of sub-milliarcsec astrometry (Figure 3.7). They determined the masses of *v And c* ( $13.98^{+2.3}_{-5.3} M_J$ ) and *v And d* ( $10.25^{+0.7}_{-3.3} M_J$ ), and their mutual inclination ( $\Delta i_{cd} = 29^\circ 9 \pm 1^\circ$ ), representing the first direct determination of relative orbit inclinations. Barnes et al. (2011c) showed that this may have arisen from scattering processes, while further evolutionary and tidal implications for this 3d orbital configuration are detailed by Deitrick et al. (2015).

*GD 66*: Constraints on the mass of the proposed companion to the pulsating white dwarf *GD 66*, inferred from the stellar pulsation arrival times, have been derived by Farihi et al. (2012c).

*HD 128311*: In an analysis along the lines of that for *v And*, McArthur et al. (2014) combined radial velocity measurements from the Hobby-Eberly and Lick 3-m telescopes with astrometric data from HST-FGS to refine the orbital parameters of the *HD 128311* system. They determined an inclination of  $55^\circ 95 \pm 14^\circ 55$  and true mass of  $3.8^{+0.9}_{-0.4} M_J$  for *HD 128311 c*, a short-period signal which could indicate a third planet, and ruled out planets b and c being in mean motion resonance.

**Other FGS astrometry** By determining  $M_p$  rather than  $M_p \sin i$ , other studies combining HST-FGS astrometry and high-precision radial velocities have identified companions as brown dwarfs or M dwarfs rather than massive planets, amongst them: *HD 33636* (Bean et al., 2007), *HD 136118* (Martoli et al., 2010), and the possibly packed system *HD 38529* (Benedict et al., 2010).

Other HST-FGS data have been acquired and are being analysed to determine masses of the Doppler-detected planets *HD 47536 b*, *HD 136118 b*, *HD 168443 c*,

*HD 145675 b*, and *HD 38529 c* (Benedict et al., 2008). Observations are also being collected for other multiple systems, including *HD 202206*,  $\mu$  Ara, and  $\gamma$  Cep, with the aim of measuring directly their co-planarity.

**WFC3** Riess et al. (2014) employed ‘spatial scanning’ with the HST-WFC3 to increase source sampling by a factor 1000. Changes in source positions with a precision of 20–40  $\mu$ as, more than a factor 10 better than in pointed observations, should allow parallax measurements of bright stars to distances of 5 kpc.

### 3.8 Astrometry from space: Hipparcos

ESA’s Hipparcos satellite was launched in 1989, and operated between 1989–93 in a 10.6-h geostationary transfer orbit, having failed to reach geostationary orbit. The final mission catalogues were published in 1997. Despite its non-nominal orbit, all of the original mission goals were substantially exceeded.

The two viewing directions were separated by  $57^\circ$ , and brought together by a 0.3-m diameter ‘beam combining’ mirror. Star images were modulated by a focal-plane grid, and detected by a combination of image dissector tube and photomultiplier detectors.

The mission provided  $\sim 1$  mas accuracy for 118 000 stars (Perryman et al., 1997a,b), modestly improved by a subsequent re-reduction (van Leeuwen, 2007), along with lower accuracy data for the Tycho and Tycho 2 catalogues (Høg et al., 1997, 2000).

The Hipparcos catalogue resulted from fitting the five parameters of the standard model ( $\alpha, \delta, \mu_{\alpha*}, \mu_\delta, \varpi$ ) to the  $\sim 100$  measurements for each star. Higher-order fits were made for 2622 stars with significant acceleration terms (either quadratic or cubic polynomials

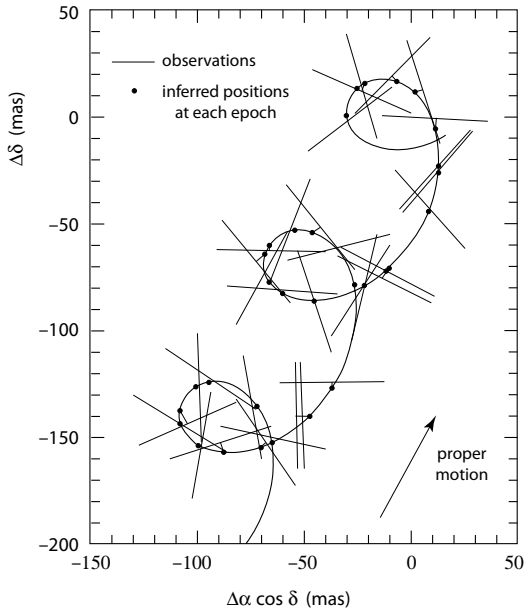


Figure 3.8: Path on the sky ( $\alpha, \delta$ ) of a Hipparcos star over 3 years. Straight lines indicate observed positions at the measurement epochs: because the measurements are one-dimensional, the location along the position line is undetermined. The curve is the modeled stellar path fitted to all measurements. Inferred positions at each epoch are indicated by the small solid circles, and the residuals by short lines joining the circles to the corresponding position lines. The amplitude of the oscillatory motion gives the star's parallax, and the linear component gives the star's proper motion. The intermediate astrometric data allow the quality of the model fit to be assessed, and possibly refined by including effects of planetary companions. The same principles apply to the Gaia intermediate astrometry. From Perryman et al. (1997b, Volume 1, Figure 2.8.1).

of time), and orbital fits for 235 stars with significant known or measured orbital motion attributable to a stellar mass companion (Lindegren et al., 1997; Perryman, 2009, Chapter 3). Planetary perturbations are barely recognisable at the milliarcsec level, and subsequent attempts to quantify any resulting astrometric motion have been carried out only in a few specific cases.

**Intermediate astrometry** In addition to the primary astrometric parameters, the catalogue includes the *intermediate astrometric data*. These are the  $\sim 100$  one-dimensional coordinates on the measurement great-circles made for each star during the observing period. Files contain the mid-epochs and poles of the reference great circle for each orbit and, within each orbit, the residuals between the observed abscissae and those calculated from the set of reference astrometric parameters given in the main catalogue (Figure 3.8).

This allows the reconstruction of the photocentric motion on the sky, as shown schematically in Figure 3.1. It also allows the Hipparcos data to be merged rigorously

with other (astrometric or radial velocity) data, or to be fit to models other than the basic fitting used to construct the Hipparcos catalogue. In the present context, periodic motion of a star due to an invisible companion whose orbital period is known, may be detectable at levels below which the star is securely identifiable as binary in the absence of such prior knowledge.

In equatorial coordinates, partial derivatives of the star abscissa can be expressed with respect to the five parameters of the standard model as

$$\begin{aligned} d_1 &= \partial a_i / \partial \alpha_*, & d_2 &= \partial a_i / \partial \delta, & d_3 &= \partial a_i / \partial \omega, \\ d_4 &= \partial a_i / \partial \mu_{\alpha*}, & d_5 &= \partial a_i / \partial \mu_{\delta}, \end{aligned} \quad (3.37)$$

where  $a_i$  is the abscissa of the  $i$ th observation of a given star. For small angles, a linearised equation for the observed abscissa difference  $\Delta a_i = a_{\text{obs}} - a_{\text{calc}}$  can then be written as (Volume 1, Section 2.8 of Perryman et al., 1997b; Goldin & Makarov, 2006)

$$\begin{aligned} \Delta a_i &= d_1 \Delta x + d_2 \Delta y + d_3 \Delta \pi + d_4 \Delta \mu_x + d_5 \Delta \mu_y \\ &+ d_1 \sum_j \frac{\partial x}{\partial \epsilon_j} \Delta \epsilon_j + d_2 \sum_j \frac{\partial y}{\partial \epsilon_j} \Delta \epsilon_j, \end{aligned} \quad (3.38)$$

where  $\epsilon_j$  are the vector components of the seven orbital elements,  $\epsilon = [P, a'', e, i, \omega, \Omega, t_p]$ , and  $x \equiv \alpha^*$ ,  $y \equiv \delta$ .

**Results** Perryman et al. (1996) derived weak upper limits on  $M_p$  for 47 UMa ( $< 7 M_J$ ), 70 Vir ( $< 38 M_J$ ), and 51 Peg ( $< 500 M_J$ ) based on adjustment of the orbital elements using a large number of trial periods, including those of the known planets. Comparable upper limits for 47 UMa were later given by Zucker & Mazeh (2001) and, following the discovery of a second planet orbiting the same system, by Fischer et al. (2002b).

Mazeh et al. (1999) used a similar approach to derive a mass for the outer companion of the 3-planet system  $\nu$  And, of  $M_p = 10.1^{+4.7}_{-4.6} M_J$ , compared with  $M_p \sin i$  from radial velocities of  $4.1 M_J$ . They also derived estimates of the mass of the two inner planets, on the assumption that the orbits of all three are co-aligned, of  $1.8 \pm 0.8 M_J$  and  $4.9 \pm 2.3 M_J$ .

A number of studies began to suggest rather high masses for some of the proposed planetary companions. For HD 10697 the companion was inferred to be a brown dwarf (Zucker & Mazeh, 2000). For  $\rho$  CrB, Gatewood et al. (2001) combined the Hipparcos intermediate astrometry with MAP data to derive a mass some 100 times larger than the minimum mass from radial velocities, although this was questioned by subsequent high-resolution infrared spectroscopy (Bender et al., 2005). Han et al. (2001b) used the intermediate astrometry for all known candidates with  $P > 10$  d to conclude that spectroscopic programmes can be biased to small values of  $\sin i$ , leading in turn to masses much in excess of the minimum masses.

Possible bias in the resulting mass estimates subsequently became the subject of some debate. Pourbaix (2001) and Pourbaix & Arenou (2001) re-analysed the same data, and argued instead that the trend to low inclinations is an artefact of the adopted fitting. This was supported by McGrath et al. (2002), who used HST-FGS observations, formally at the level of 0.3 mas, to examine the motion of 55 Cnc. They placed  $3\sigma$  upper limits of 0.3 mas on the reflex motion, ruling out the 1.15 mas perturbation proposed by Han et al. (2001b), and placing an upper limit of about  $30 M_J$  on the planetary mass.

**Other mass constraints from Hipparcos:** Mass limits for other planet candidates discovered from radial velocity observations include: HD 179949 and HD 164427 (Tinney et al., 2001); HIP 75458/*ι* Dra (Frink et al., 2002); and HD 11977 (Setiawan et al., 2005). Zucker & Mazeh (2001) analysed Hipparcos astrometry for 47 planet and 14 brown dwarf secondaries, finding that the lowest derived upper limit is for 47 UMa at  $0.014 M_{\odot}$ , similar to the limits given by Perryman et al. (1996). For 13 other candidates, upper limits were able to exclude a stellar companion.

The intermediate astrometric data were used to constrain, or in three cases solve for, the orbital inclinations and masses for a further ten low-mass companions from the Keck precision radial velocity survey (Vogt et al., 2002). Astrometric orbital solutions for a few Doppler-detected systems containing companions with minimum masses close to and slight above the dividing line between planets and brown dwarfs have been obtained by Reffert & Quirrenbach (2006) and Sozzetti & Desidera (2010).

Reffert & Quirrenbach (2011) used the intermediate astrometry from the re-reduction of van Leeuwen (2007) to derive mass constraints and astrometric signatures for 310 planets and brown dwarfs companions (in 258 systems) discovered by radial velocity measures. They set upper mass limits for 243, confirming 9 as planets (Pollux,  $\epsilon$  Ori,  $\epsilon$  Ret,  $\mu$  Ara,  $v$  And, 47 UMa, HD 10647 and HD 147513), and detecting astrometric signatures in a further 20 objects.

Sahlmann et al. (2011a) determined  $i = 178.3^{+0.4}_{-0.7}$  deg for the radial velocity candidate HD 5388 b ( $M_p \sin i = 1.96 M_J$ ), implying  $M_p = 69 \pm 20 M_J$ , and thereby excluding a planetary mass companion. The fit is good even though the astrometric orbit,  $a = 1.7 \pm 0.5$  mas, is small compared to the median single-measurement precision (3.8 mas).

Various studies illustrate the rigorous use of combined radial velocity and astrometric data. Hauser & Marcy (1999) concluded that their combined results were consistent with perturbations from 16 Cyg A causing the eccentricity of the planet around 16 Cyg B.

Torres (2007a) used a combination of radial velocities and Hipparcos astrometry in a study of the orbit of  $\gamma$  Cep. The minimum mass of the companion is  $M_p \sin i = 1.43 \pm 0.13 M_J$  from the radial velocity data alone, while the Hipparcos astrometric data place a dynamical upper limit on this mass of  $13.3 M_J$ .

Various useful inferences about systems discovered by radial velocity measurements have since been made using Hipparcos data (box, page 95). But it is evident from Equation 3.1 (and Figure 3.9) that milliarcsec astrometry can contribute only marginally to exoplanet detection and orbit characterisation.

### 3.9 Astrometry from space: Gaia

Building on Hipparcos, the Roemer mission was submitted to ESA in 1992, in an unsuccessful proposal led by Erik Høg, a key figure in space astrometry (Høg & Lindegren, 1994). The yet more ambitious Gaia mission was proposed by Lennart Lindegren and Michael Perryman in 1993, leading to a detailed concept and technology study and comprehensive scientific case (Perryman et al., 2000). Gaia was accepted by ESA's Science Programme Committee in 2000 (Perryman et al., 2001), and

launched, within a year of its originally targeted date, in December 2013. The nominal mission duration was 5 years, with an extension to end 2020 approved in 2017. Operations for 10 years (i.e., until 2023–24) are consistent with on-board consumables.

Large-scale microarcsec astrometry will contribute to exoplanet science at many levels: (a) it provides fundamental data to quantify host star properties (§8.1); (b) it provides planet detection possibilities out to 50–200 pc; (c) with spectroscopic measurements and an estimated host star mass, it yields the planet mass irrespective of orbit inclination; (d) relative orbit inclinations of multi-planet systems can be determined in favourable cases; and (e) planet-induced astrometric lensing should be detectable in a few cases (§5.8).

#### 3.9.1 Principles

Gaia follows the same principles as Hipparcos: a sky-scanning mission, above the Earth's atmosphere (but at the Langrange point L2), with two widely separated fields of view ( $106^\circ$ , compared to  $57^\circ$  for Hipparcos). The improvement in astrometric accuracy of some two orders of magnitude, and a detection limit more than 8 mag fainter, result primarily from a combination of increased primary mirror size (from 0.3 m diameter to  $1.45 \times 0.5 \text{ m}^2$ ), detector size and efficiency (with photocathodes replaced by 106 CCDs each of  $4500 \times 1966$  pixels covering  $0.5 \times 1.0 \text{ m}^2$ ), and multiplexed (rather than sequential) star observations (Perryman et al., 2001; Gaia Collaboration et al., 2016b). Astrometric observations are made in a broad optical band, designated *G*, and to first order comparable to Johnson *V*.

On-board object detection, as the star images enter the fields of view, avoids the need for a pre-defined observing programme, and allows Gaia to survey more than a billion stars to a completeness limit of  $G \sim 20 - 21$  mag. Around 80 distinct astrometric measurements will be made for each star over the nominal 5-yr mission (the number varies with ecliptic latitude), with a magnitude-dependent single-measurement accuracy determined by the image centroid accuracy derived from a focal plane scan.

Final astrometric accuracies (in positions, parallaxes, and annual proper motions; again, for the nominal 5-yr mission duration) should be roughly constant at  $\sim 10 \mu\text{as}$  between  $V \sim 7 - 12$ , degrading according to photon statistics to  $\sim 20 - 25 \mu\text{as}$  at  $V = 15$ , and to  $\sim 300 \mu\text{as}$  at  $V = 20$  (depending on photometric passband, star colour, and astrometric parameter). Final accuracies result from the combination of the one-dimensional measurements over the mission, assembled through a multi-parameter global iterative adjustment which also calibrates attitude motion and optical distortions, including chromatic terms (Perryman et al., 2001; O'Mullane et al., 2011; Lindegren et al., 2012).

**Gaia: photometry and radial velocities:** Two other instruments occupy the focal plane. Multi-epoch multicolour photometry for all stars is provided by low-resolution spectrophotometry in red and blue channels at the trailing edge of the astrometric field (see Jordi et al., 2010, Figs 1–2), yielding information on the star spectral type, luminosity class, and associated interstellar reddening, along with spectral data sufficient for chromatic correction for the primary astrometric measurements.

The highest photometric accuracy is achieved from the unfiltered *G* band astrometric field photometry, and ranges (per field crossing) from 1 mmag or better for  $G < 14$  mag to  $\sim 0.2$  mag at  $G = 20$  mag (Jordi et al., 2010, Figure 19).

The Radial Velocity Spectrometer (RVS) is a  $2.0 \times 1.6 \text{ deg}^2$  integral field spectrograph with resolving power  $R = \lambda/\Delta\lambda = 11500$ . It operates at 848–874 nm, centred on the Ca II diagnostic triplet (Katz et al., 2004; Wilkinson et al., 2005; Cropper et al., 2018). It is collecting spectra of 100–150 million stars to  $V \lesssim 17 - 18$  mag, each observed some 100 times on average over 5 years.

Predicted mission-level performances include: (a) radial velocities of  $\sim 2 \text{ km s}^{-1}$  at  $V = 15$ , and  $\sim 15 - 20 \text{ km s}^{-1}$  at  $V = 17$ , for a solar-metallicity G5 dwarf; (b) rotational velocities of  $\sigma_{v \sin i} \sim 5 \text{ km s}^{-1}$  at  $V = 15$  (for late-type stars) as well as atmospheric parameters for  $V \lesssim 14 - 15$ ; (c) abundances of the  $\alpha$ -elements, such as Si and Mg, important for studies of Galactic evolution, for  $V \lesssim 12 - 13$ .

Extensive simulations of the entire sky distribution, observing and data processing chain are part of the very substantial scientific framework established for the Gaia mission, and the entire mission data processing centres around the global iterative solution, with ‘peripheral tasks’ interfacing with the central database, with the photometric, multiple star, and planet detection and characterisation modules all part of the global analysis.

For the astrometric planet detection, some independent simulations and algorithmic fits have also been reported (Huang & Ji, 2016; Xu et al., 2016b; Huang & Ji, 2017; Xu et al., 2017c).

### 3.9.2 Expected astrometric planet yield

The numbers of astrometric exoplanet discoveries with Gaia is expected to be significant, of order several thousand. Details depend on the ultimate astrometric performance of the instrument, the mission duration, and the (unknown) planetary distributions (including multiplicity) at the orbital periods (1–5 yr) and mass ranges ( $1 - 5 M_J$ ) most relevant. Astrometric discoveries will most probably only be announced after several years of data have been acquired and analysed, perhaps around 2022, although some earlier results may be anticipated.

**Early assessments** The astrometric detection of exoplanets figured in the original scientific case for Gaia, which accompanied the concept and technology study (Perryman et al., 2000, 2001). Estimates of 10–50 000 detectable systems were based star counts from the Besançon Galaxy model, a distance horizon of 200 pc corresponding to F0–K5 dwarf stars at  $V \lesssim 12$  mag,

an effective frequency of Jupiter-type planets of 1.3%, and periods and astrometric signatures in the range  $0.5 < P < 20$  yr and  $10 < \alpha < 100 \mu\text{as}$ . Subsequent assessments (Lattanzi et al., 2000; Quist, 2001; Sozzetti et al., 2001) also employed the target astrometric accuracies at the time of mission acceptance, which were descoped in 2002 and 2004. All were based on the limited knowledge of exoplanet occurrence (as a function of stellar spectral type, and planetary orbit properties) at the time.

Casertano et al. (2008) made a detailed 5-yr mission simulation, and focused on a double-blind protocol for assessing the significance of the solutions. Their numerical yield was based on star counts from the Besançon Galaxy model, but restricted to FGK dwarfs, and to  $V < 13$  and  $d < 200$  pc to provide constant astrometric precision and hence uniform Gaia detectability thresholds for their orbit-fitting experiments. Their adopted along-scan single-epoch measurement error of  $\sim 11 \mu\text{as}$  ( $\sim 8 \mu\text{as}$  for successive crossings of the two fields of view) is a factor 3 better than the later pre-launch estimates of  $\sim 34 \mu\text{as}$ , even for the brightest Gaia stars.

They showed that planets with astrometric S/N  $> 3$  per field crossing and period  $P \leq 5$  yr can be detected reliably and consistently, with a very small number of false-positives. At twice the detection limit, they found uncertainties in orbital parameters and masses of typically 15–20%, while for favorable two-planet systems orbital elements will be measured to better than 10% accuracy in some 90% of cases, with the mutual inclination angle  $\Delta i$  determined with uncertainties  $\lesssim 10^\circ$ .

**Pre-launch assessment** Perryman et al. (2014a) made a comprehensive re-assessment of the astrometric yield, taking into account: (a) a broad host star parameter range (in spectral type and distance), based on the Galaxy population model TRILEGAL (box, page 380); (b) revised estimates of exoplanet occurrences as a function of host star and planet properties; (c) pre-launch instrument performance estimates; and (d) detailed simulations of the satellite scanning law. Given the very large number of exoplanets which should be detected (15–30 000 for the nominal 5-yr mission, rising to more than 50 000 for an extended 10-yr mission) some further details underlying these estimates are given.

For the assumed exoplanet occurrence dependencies, for each of the 260 million stars returned by the TRILEGAL Galaxy simulations to  $r < 17.5$ , planets were simulated with best estimates from the literature on host star mass and metallicity, planet mass and orbital period, occurrences around M dwarfs, and orbit eccentricities following a Beta distribution (§2.10.4). Simplistic assumptions were adopted for planets around binary stars (where the secondaries were ignored), and for multi-planet systems.

Relevant quantities for the Gaia accuracy predictions are (Perryman et al., 2014a, Eqns 1–4)

$$z = 10^{0.4(\max[G,12]-15)}, \quad (3.39)$$

$$\sigma_\eta = (53\,000 z + 310 z^2)^{0.5} \mu\text{as}, \quad (3.40)$$

$$\sigma_{\text{fov}} = \left( \frac{\sigma_\eta^2}{9} + \sigma_{\text{att}}^2 + \sigma_{\text{cal}}^2 \right)^{0.5} \mu\text{as}, \quad (3.41)$$

$$\sigma_\odot = 1.2 \times 2.15 \sigma_{\text{fov}} / \sqrt{68.9} = 0.311 \sigma_{\text{fov}} \mu\text{as}. \quad (3.42)$$

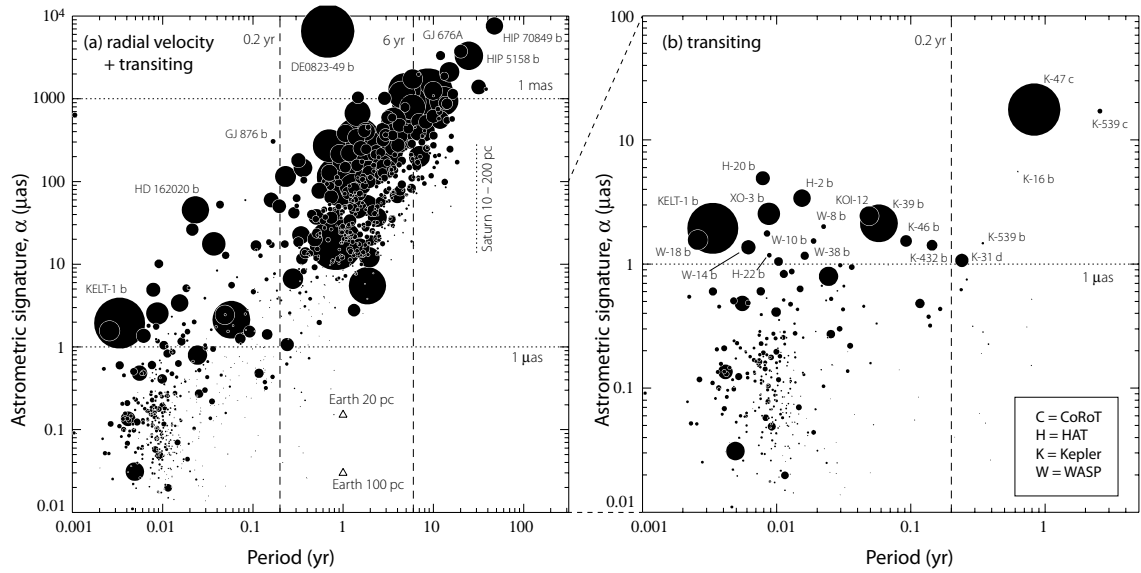


Figure 3.9: Astrometric signature,  $\alpha$ , versus period (Equation 3.1) for radial velocity and transiting planets (left), and for transiting planets only (right, at different scales), for systems from the NASA Exoplanet Archive at 2017 December 31. Circles are proportional to  $M_p$  (or  $M_p \sin i$ ). (a) The 600 radial velocity and 350 transiting planets having data needed to estimate  $\alpha$ . Some specific objects, and the effects of Earth and Saturn at various distances, are labeled. Vertical lines at 0.2 and 6 yr are indicative detection limits for Gaia. Horizontal lines show astrometric signatures of 1 mas and 1  $\mu\text{as}$ ; the lower limit for Gaia is  $\sim 30 \mu\text{as}$ . (b) The subset of planets discovered as transiting. Those with  $\alpha > 1 \mu\text{as}$  are labeled by (abbreviated) star name (see legend). Many imaging discoveries will also have large  $\alpha$ , but with generally (very) large orbital periods.

Here,  $z$  is the (relative) number of photons in the image, normalised to  $z = 1$  at  $G = 15$ ;  $\sigma_\eta$  is (a polynomial fit to) the centroiding accuracy for each of the nine along-scan CCDs in the astrometric field;  $\sigma_{\text{fov}}$  is the along-scan accuracy per field of view passage, with provisional estimates of the attitude errors,  $\sigma_{\text{att}} = 20 \mu\text{as}$  (Risque et al., 2013), and similarly for the calibration errors,  $\sigma_{\text{cal}}$ ; and  $\sigma_\omega$  (included for reference) is the sky-averaged parallax accuracy for the nominal mission duration of 5 yr. In Equation 3.42, 2.15 is a geometric factor linking the (sky-averaged) parallax accuracy with the error per field crossing, 68.9 is the (sky-averaged) number of field crossings per star over the nominal 5-yr mission including dead time, and 1.2 is a margin.

For each simulated star–planet system, the astrometric signature can be calculated from Equation 3.1 and the planet considered as ‘potentially detectable’ if it exceeds a suitable S/N threshold per field crossing

$$S/N \equiv \alpha / \sigma_{\text{fov}} > n. \quad (3.43)$$

This zero-order indicator of detectability is one which, in reality, depends on the number and distribution of observations, the system’s inclination and eccentricity, and the orbital period compared to the observational span.

Planet detectability can be better quantified through orbit reconstruction based on simulated data. The Gaia AGISLab project (Holl et al., 2012) allows the simulation

of individual CCD transits of millions of sources, using a comprehensive instrument model. This can be used to generate, for any target star based on its sky coordinates, the attributes of all field crossings over the mission. These, together with the assumed along-scan standard error per field crossing (as a function of  $G$ ), and the seven specified orbital elements of the star’s reflex motion, allow simulation of fully representative intermediate astrometry observations.

Orbit fitting then aims to recover the 7 Keplerian parameters: either the classical elements  $a, e, P, i, \Omega, \omega$  (Section 2.1.1), or the four Thiele–Innes constants  $A, B, F, G$  (themselves functions of  $a, i, \Omega, \omega$ ; cf. §3.4) together with the frequency  $f = 1/P$ , eccentricity  $e$ , and mean anomaly at the reference epoch,  $M_0$ . Use of the Thiele–Innes constants means that the least-squares problem is non-linear only in the last three parameters  $f, e$ , and  $M_0$  (Perryman et al., 2014a, Appendix A).

**Detection details** A more precise criterion of detectability is then given by the test statistic for the significance of the orbit, viz. the reduction in minimum  $\chi^2$  going from the standard 5-parameter astrometric solution to the 12-parameter solution including the 7 Keplerian elements

$$\Delta\chi^2 = \chi^2_{\text{min}}(5 \text{ parameter}) - \chi^2_{\text{min}}(12 \text{ parameter}). \quad (3.44)$$

In contrast to the S/N,  $\Delta\chi^2$  can be calculated for real data, i.e. without knowledge of the orbit. Evidently,  $\Delta\chi^2$  can be small even when  $\alpha / \sigma_{\text{fov}}$  is very large, e.g. if the observations cover

Table 3.2: Estimates of the number of astrometric detections with Gaia.  $N_\star$  gives the total host star numbers from the TRILEGAL Galaxy simulations (all spectral types).  $N_{\text{det}}$  and  $N_{\text{tran}}$  are the planets detected and transiting for various S/N thresholds,  $\alpha/\sigma_{\text{fov}}$  (Equation 3.43). The lower part of the table gives the cumulative numbers, at that S/N, which also pass detection defined by  $\Delta\chi^2$  (Equation 3.44). Best estimates of  $N_{\text{det}}$  and  $N_{\text{tran}}$  are in bold. Results are given for the nominal 5-yr mission, and for an extended 10-yr mission. Adapted from Perryman et al. (2014a, Table 4).

$\Delta d$ (pc)	$N_\star$	$N_{\text{det}}$ $\alpha > 0.5\sigma_{\text{fov}}$	$N_{\text{tran}}$ $\alpha > 0.5\sigma_{\text{fov}}$	$N_{\text{det}}$ $\alpha > 1\sigma_{\text{fov}}$	$N_{\text{tran}}$ $\alpha > 1\sigma_{\text{fov}}$	$N_{\text{det}}$ $\alpha > 2\sigma_{\text{fov}}$	$N_{\text{tran}}$ $\alpha > 2\sigma_{\text{fov}}$	$N_{\text{det}}$ $\alpha > 3\sigma_{\text{fov}}$	$N_{\text{tran}}$ $\alpha > 3\sigma_{\text{fov}}$	$N_{\text{det}}$ $\alpha > 6\sigma_{\text{fov}}$	$N_{\text{tran}}$ $\alpha > 6\sigma_{\text{fov}}$
0–50	39 000	1508	5.4	897	2.8	512	1.4	359	0.9	186	0.4
50–100	203 000	5914	20.6	3344	9.9	1789	4.4	1195	2.6	502	0.9
100–150	476 000	8598	30.1	4877	14.3	2435	5.8	1466	3.0	452	0.7
150–200	889 000	11737	37.2	6309	16.7	2851	6.2	1589	3.1	289	0.4
200–250	859 000	8976	26.9	4601	11.5	1860	3.8	862	1.5	51	0.0
250–300	1 298 000	11734	33.8	5677	13.5	2026	4.0	832	1.5	12	0.0
300–350	1 793 000	14972	42.2	6857	15.9	2008	3.8	636	1.0	–	–
350–400	1 775 000	13091	35.7	5464	12.4	1308	2.4	264	0.4	–	–
400–450	1 411 000	9019	24.3	3394	7.5	642	1.2	63	0.1	–	–
450–500	1 718 000	10439	27.3	3691	8.0	533	1.0	25	0.0	–	–
500–600	4 267 000	21172	53.8	6411	13.9	572	1.1	8	0.0	–	–
600–700	5 732 000	21286	53.7	4984	10.9	127	0.3	–	–	–	–
700–800	5 462 000	15434	37.9	2678	5.9	5	0.0	–	–	–	–
800–1400	36 500 000	35219	88.0	2083	4.7	–	–	–	–	–	–
Total	62 000 000	189099	517	61267	148	16668	35	7299	14	1492	2
$\Delta\chi^2$	$N_{\text{det}}$ $\alpha > 0.5\sigma_{\text{fov}}$	$N_{\text{tran}}$ $\alpha > 0.5\sigma_{\text{fov}}$	$N_{\text{det}}$ $\alpha > 1\sigma_{\text{fov}}$	$N_{\text{tran}}$ $\alpha > 1\sigma_{\text{fov}}$	$N_{\text{det}}$ $\alpha > 2\sigma_{\text{fov}}$	$N_{\text{tran}}$ $\alpha > 2\sigma_{\text{fov}}$	$N_{\text{det}}$ $\alpha > 3\sigma_{\text{fov}}$	$N_{\text{tran}}$ $\alpha > 3\sigma_{\text{fov}}$	$N_{\text{det}}$ $\alpha > 6\sigma_{\text{fov}}$	$N_{\text{tran}}$ $\alpha > 6\sigma_{\text{fov}}$	
nominal 5-year	> 30	<b>27505</b>	<b>42</b>	26038	42	12893	25	6541	12	1475	2
"	> 50	<b>14806</b>	<b>25</b>	14755	25	10297	20	5762	10	1444	2
"	>100	6488	11	6488	11	6116	11	4393	8	1353	2
extended 10-year	> 30	<b>90751</b>	<b>135</b>	58674	117	16666	35	7299	14	1492	2
"	> 50	<b>53015</b>	<b>82</b>	47630	80	16648	35	7299	14	1492	2
"	>100	25958	39	25882	39	15836	30	7285	14	1492	2

only a small part of the orbit, while for a given S/N per field crossing,  $\Delta\chi^2$  increases with the number of observations.

Table 3.2 shows the results of these simulations as a function of star distance, S/N threshold, and mission duration. The lower part of the table gives the cumulative numbers, at each given S/N, which also pass detection defined by  $\Delta\chi^2$  (Equation 3.44). Some planets remain detectable down to  $\alpha/\sigma_{\text{fov}} \sim 0.5$  while, below this, increasing fractions fail the  $\Delta\chi^2$  test.

Best estimates of  $N_{\text{det}}$  are given in bold, suggesting that some 21 000 ( $\pm 6000$ ) planets should be detectable for the nominal 5-yr mission, depending on the adopted value of  $\Delta\chi^2$ . Indicatively, they are 5–10  $M_J$  planets out to a distance  $d \sim 200$ –500 pc. A significant fraction should have well-determined orbits, although systems with  $P \gtrsim 6$  yr (for the nominal 5 yr mission) will be poorly constrained.

These predicted numbers still rest on numerous assumptions, including the underlying Galaxy model, the planet occurrence distributions, and the detailed astrometric performances of Gaia. Bottom-line numbers are in tolerable numerical agreement with the estimated yield at the time of the mission's acceptance in 2000, although the details are substantially different.

**M dwarfs** Sozzetti et al. (2014) showed that Gaia should detect  $\sim 100$  giant planets across the known sample of M dwarfs within 30 pc, and some 2600 detections and  $\sim 500$  accurate orbits out to 100 pc. Results for M dwarfs from the broader Galaxy models of Perryman et al. (2014a) give comparable numbers (their Table 5), suggesting that at least 1000–1500 planets should be detectable around M dwarfs out to  $\sim 100$  pc.

**Mission extension** Gaia has the potential to observe for considerably longer than the nominal 5 years. A longer mission would bring substantial improvements for the detection, orbit determination, and period coverage, suggesting yields of some 70 000 ( $\pm 20000$ ) exoplanets for a 10-yr mission.

To underline the future prospects for astrometry, the factor of 2.5 improved accuracy that was the original Gaia objective when accepted by the ESA advisory committees in 2000 (10  $\mu\text{s}$  at 15 mag) would formally extend the volume of space surveyed at a given relative distance accuracy by a factor 2.5<sup>3</sup>. Taking into account the scale height of the Galactic disk and the distance distribution of detected planets, the detection statistics above would all be scaled up by a further factor of roughly 2.5<sup>2</sup>  $\sim 6$ .

**Constraints from Hipparcos and Gaia** Long-period binary and exoplanetary candidates may give rise to observable effects well below the limit of Gaia detectability alone. For a  $1M_\odot$  star at 10 pc distance with an invisible companion of mass  $M_p$  with  $P \sim 25$  yr, the ‘instantaneous’ proper motion of the star relative to the barycentre (i.e., as measured by Hipparcos) is  $2\pi a_\star/P \sim 200(M_p/M_\odot)$  mas yr<sup>-1</sup>. Over 25 yr, the extrapolated position compared to that observed by Gaia could differ by up to  $5000(M_p/M_\odot)$  mas. If detection is possible for a positional difference of twice the combined uncertainty, companion masses down to  $\sim 10^{-2}M_\odot$ , viz. of brown dwarf or super-Jupiter mass, could be detected.

With 2–3 yr of Gaia data, the expected proper motions (from Gaia alone) should be better than 30  $\mu\text{s}$  yr<sup>-1</sup> for bright stars, and the inverse formulation (extrapolating the signifi-

cantly more accurate Gaia proper motions back to the Hipparcos Catalogue epoch) becomes considerably more probing. The resulting positional difference sensitivity increases by a factor 30, suggesting the large-scale detection of (or constraints on) companion masses down to  $\sim 3 \times 10^{-4} M_{\odot}$ , viz. Saturn-type objects at very wide (Saturn-like) distances from its host star.

**Circumbinary planets** Kepler and other results suggest a minimum occurrence of circumbinary giant planets of  $\sim 10\%$ , yet only a small number are presently known (§6.31). Sahlmann et al. (2015) estimated Gaia’s discovery space for circumbinary planets around nearby binary stars by detecting the binary’s periodic astrometric motion caused by the orbiting planet, adopting the criterion of Equation 3.43 with  $n = 20$ . They estimated that Gaia will discover hundreds of giant planets around binaries with FGK dwarf primaries within 200 pc, on the assumption that the giant planet mass distribution and abundance are similar around binaries and single stars, but only some four detections if all circumbinary gas giants have  $M_p < 2M_J$ .

**Characterising the brown dwarf desert** A prominent feature of radial velocity surveys is the absence of close-in ( $a < 3 - 4$  au) substellar objects in the range  $10 - 80M_J$ , the ‘brown dwarf desert’ (§2.10.5). With an occurrence rate of  $\lesssim 0.3 - 0.6\%$  for  $P \sim 300$  d around solar-type stars, only some 60–70 are known. The population is poorly characterised, and its place in the scheme of planet formation is not well established. Although no specific simulations of detection rates with Gaia have been reported, brown dwarf companions to solar-type stars will induce particularly prominent reflex motions in their host stars, and should be easily detected. Some tens of thousands of desert occupants might be expected to  $V \sim 15$  mag.

**Complimentarity with other observations** A substantial range of new cross-disciplinary studies will become possible with Gaia astrometry, including (as examples) the combination with radial velocity observations, with VLT-SPHERE and Gemini-GPI imaging, and more detailed characterisation of the Kepler and other transiting planets.

### 3.9.3 Transiting planets from Gaia astrometry

Few, if any, of the planets discovered to date by ground- or space-based photometric transit searches will induce measurable astrometric displacements on their host stars, due to their typically small semi-major axes and low masses (Figure 3.9b). Long-period transiting planets will also probably remain elusive even with future transit surveys. Thus, the Gaia *photometric* transit discoveries are likely to be restricted to  $P \lesssim 5 - 10$  d (§6.8.2), with the TESS survey (§6.8.1) and the planned HATPI survey (§6.4.4) perhaps extending this to  $P \approx 40 - 50$  d. PLATO (§6.8.1) is expected to extend the discovery space out to 1 au or so.

In this context, an interesting class of transiting planet should be discovered from Gaia *astrometry*, viz. systems with large  $\alpha$  which can be inferred, either statistically, or explicitly from their reconstructed orbit parameters, to lie edge-on to the line-of-sight (Perryman et al., 2014a). The statistical existence of such astrometric transiting planets was also noted by Sozzetti et al. (2014) in their assessment of giant planets around M dwarfs detectable by Gaia.

Estimated numbers,  $N_{\text{tran}}$ , are given in Table 3.2. Plausibly, some 25–42 detected systems with  $i \approx 90^\circ$  should harbour transiting planets, with one or two such transits also being present in the Gaia multi-epoch photometry. The systems have periods of a few years, a mean transit duration of 0.89 d, and a mean duration as a fraction of the orbital period of 0.000 64.

While their identification will not be straightforward due to the relatively large errors on  $i$  and  $t_{\text{transit}}$ , the transit depths,  $\Delta F \equiv (R_p/R_\star)^2$  (Equation 6.8), will often be large because of their large masses and radii. The predicted distribution has a median of 0.008, increasing steeply for small values, but showing a few very pronounced transits,  $\Delta F \sim 0.01 - 0.1$ , compared with the deepest currently known of  $\sim 0.03$  for HATS-6 b, (Hartman et al., 2015b). The most prominent are long-period massive planets ( $1 - 10M_J$ ) around the nearby ( $d \lesssim 100$  pc) lowest mass ( $\lesssim 0.35M_{\odot}$ ) M dwarfs.

A single transit per candidate system would provide improved prospects for estimating the radii and densities of an important class of the exoplanet population unexplored to date.

Simulations of a 5-yr HAT-PI survey (§6.4.4) suggest that a dozen of these long-period planets might be detected photometrically (Hartman, priv. comm., 2016). Candidates may show transits in other large-scale surveys, such as the All-Sky Automated Survey for SuperNovae (ASAS-SN; Shappee et al., 2014; Holoién et al., 2017), operational since 2014, and currently employing 20 0.14-m telescopes to survey the full sky with a 2–3-d cadence to  $V \sim 17$ .

Amongst other applications, these transiting systems should be well suited to the types of atmospheric analyses offered by atmospheric refraction and stellar mirages (§6.14.11), and for the detection of associated exoplanet rings (§6.14.5).

### 3.9.4 Data releases

The first release of Gaia astrometry data, DR1, was in 2016Q3 (Gaia Collaboration et al., 2016a,b). It contains positions and magnitudes for  $\sim 1.1 \times 10^9$  stars to  $G \lesssim 20.7$  mag from the first 14 months of mission observations (Lindegren et al., 2016; Evans et al., 2017).

For the 2 million brightest stars in common with the (Hipparcos) Tycho 2 Catalogue, their combination in the Tycho–Gaia astrometric solution (TGAS) provides positions and parallaxes at  $\sim 0.3$  mas, and proper motions around  $1 \text{ mas yr}^{-1}$ . For a subset of the 94 000 stars in common with the Hipparcos Catalogue, and by exploiting the epoch difference between the two catalogues of almost 25 yr, the proper motions are around  $0.06 \text{ mas yr}^{-1}$  (cf. Michalik et al., 2014).

Gaia Data Release 2, DR2, made available on 2018 April 26 as this volume goes to press, contained the first (preliminary) parallaxes.

## 3.10 Other space astrometry projects

### 3.10.1 Proposed space missions

**JASMINE** The JASMINE series has three components: Nano-JASMINE (Japan Astrometry Satellite Mission for INfrared Exploration) is a small (0.05-m primary) sky-scanning (Gaia-like) experiment in the  $z$ -band, aiming

for accuracies of 3 mas (Kobayashi et al., 2008). As of early 2018, it is awaiting launch. Further in the future, Small-JASMINE (0.3-m primary) and JASMINE (0.8-m primary) are proposed near-infrared pointed missions, focusing on the Galactic centre, and with target accuracies of  $10 \mu\text{as}$  (Gouda et al., 2008; Gouda, 2015).

**GaiaNIR** Proposed new technology studies, submitted to ESA in June 2016, and referred to as GaiaNIR, target the development of near-infrared astrometry with a focus on more obscured Galactic regions including the Galactic centre (Hobbs et al., 2016).

**Theia** Theia was proposed as medium mission M5 in ESA's Cosmic Vision 2015–2025 (Malbet et al., 2016; Boehm et al., 2017). Using an on-axis TMA concept with extensive metrology, it targets sub- $\mu\text{as}$  relative astrometry on very faint objects, with a scientific case embracing nearby Earth-like exoplanets as well as local dark matter.

### 3.10.2 Projects no longer under consideration

Various space astrometry concepts, which have included planet detection amongst their objectives, were inspired by the success of Hipparcos, and studied from the mid-1990s, but are no longer under consideration.

**Sky-scanning and step-stare concepts** The German sky-scanning DIVA project targeted 0.2 mas accuracy to 15 mag (Röser, 1999). Russian studies included LIDA and OSIRIS-Astrometria (Bagrov, 2006), with the latter included in the Roscosmos outline for space projects for the coming decade.

Several projects were studied and initiated by the US Naval Observatory, but all were eventually cancelled. MAPS was designed to operate in a *step-stare* mode (Zacharias & Dorland, 2006). The *sky-scanning* projects were: FAME targeting 10 million stars to 14 mag (Johnston, 2003); AMEX and OBSS reaching to 23 mag (Johnston et al., 2006b); and JMAPS (Joint Milliarcsecond Pathfinder Survey) targeting some 20 million stars to  $V = 14$  mag at  $\sim 1$  mas accuracy (Dorland et al., 2009; Hennessy et al., 2010; Zubko et al., 2015), cancelled in mid-2012.

NEAT (Nearby Earth Astrometric Telescope) was proposed as an unsuccessful candidate for medium mission M3 in ESA's Cosmic Vision 2015–2025 (Shao et al., 2011; Malbet et al., 2012a,b). The goal was to detect and characterise planets down to  $1M_{\oplus}$  in the habitable zone around 200 nearby FGK stars, targeting 50 visits each, and with single-visit accuracies of  $0.05 \mu\text{as}$ . Technical implementation called for a 1-m off-axis parabolic telescope, and a wide-field detector 40 m away (to provide adequate angular resolution, and calling for formation flying or a deployable boom), and comprising 8 movable CCDs located around a fixed central CCD. An interferometric calibration system would monitor dynamical Young's fringes originating from metrology fibers at the primary mirror. Technical challenges included maintaining errors below  $1 \mu\text{as}$  over a 30 arcmin field (to provide a reference star grid, and implying stability of  $10^{-10}$  over a 5-yr lifetime), and image centroiding to  $10^{-5}$  pixels for a diffraction-limited, Nyquist sampled, focal plane.

In another approach to the sub- $\mu\text{as}$  calibration of optical distortions, Guyon et al. (2012a) proposed adding a grid of small regularly-spaced dark spots to the primary mirror surface, yielding a *diffractive pupil telescope* with a grid of faint stellar

diffraction spikes on the same focal plane detector as the background stars. The inclusion of coronagraphic imaging is described by Guyon et al. (2013).

The Gravitation Astrometric Measurement Experiment (GAME) proposed the use of differential astrometry and coronagraphy for measurement of the  $\gamma$  and  $\beta$  parameters of the Parameterised Post-Newtonian formulation of gravity, but also addressing exoplanets (Gai et al., 2012).

China's STEP (Search for Terrestrial Exo-Planets) targets  $1 \mu\text{as}$  for exoplanet detection (Chen et al., 2013a; Chen, 2014).

**Interferometric concepts** NASA's Space Interferometry Mission (SIM), and its subsequent configurations (SIM PlanetQuest and SIM Lite), was a pointed (Michelson) interferometer, originally with a 10-m baseline, which started development in 1996, based on concept studies made several years earlier (Shao, 1993). In a revised configuration, SIM PlanetQuest (Unwin et al., 2008) targeted parallaxes at about  $4 \mu\text{as}$  for  $V \leq 20$ , and a differential accuracy of  $0.6 \mu\text{as}$  on bright stars. A further redesign, SIM Lite, had a shorter 6-m baseline, and consisted of two Michelson interferometers and a precision telescope working as a star tracker (Goullioud et al., 2008). It targeted sub- $\mu\text{as}$  narrow-angle astrometry in 1.5 h on bright targets ( $V \leq 6$ ) linked to fainter reference stars ( $V \approx 9 - 10$ ) in a  $2^\circ$  field.

Various assessments of SIM's planet detection and characterisation performance were made (Sozzetti et al., 2002, 2003; Ford & Tremaine, 2003; Ford, 2004a, 2006a; Catanzarite et al., 2006; Unwin et al., 2008; Brown, 2009a; Traub et al., 2010; Gregory, 2011a). The pointed capability meant that it would be optimised for detailed orbit determinations of targeted planetary systems, and the reference mission included a survey of 65 nearby stars over 5 years. Another optical interferometer study, Planet Hunter, was carried out at JPL as a NASA astrophysics strategic mission concept (Marcy, 2009b).

The 'ultimate' goal of the astrometric detection of an Earth-like planet in the habitable zone nevertheless represented a major challenge. Traub et al. (2010) used detailed double-blind simulations to conclude that some 250 visits to a given star over the mission lifetime, each of differential accuracy  $\sigma_{\psi} = 1.4 \mu\text{as}$  along one axis, and the addition of 15 years of radial velocity observations to assist characterisation of any long-period planets in the system, would be required to detect Earth-like planets in the presence of other orbiting planets.

Despite being endorsed by two US Decadal Surveys, and having progressed through Phases A and B (at a cost of \$600M, Horzempa, 2012), interferometric space astrometry did not appear as a high priority in the 2010 Decadal Survey report (Blandford et al., 2010), and was subsequently abandoned.

## 3.11 Radio and sub-mm astrometry

### 3.11.1 Astrometry at radio wavelengths

For stars that are themselves significant and compact sources of radio emission, planet detection may be possible using the measured astrometric displacements of the host star. As in optical astrometry, sub-mas (and preferable  $\mu\text{as}$ ) positional accuracy is required at a number of suitably spaced measurement epochs. From them, the five astrometric parameters (two positional components, two proper motion components, and parallax) as well as the star's reflex motion due to the orbiting planet, can in principle be derived.



**Radio astrometry targets:** Various stellar types have been considered as targets for high-accuracy radio astrometry, and for the associated search for orbiting exoplanets:

*Late-type stars:* for 51 F, G, and K stars, including single stars (giants, subgiants and dwarfs), active components of close binaries, and the Sun, Stewart et al. (1988) found a relation between peak radio luminosities at 8.4 GHz ( $\lambda = 3.6$  cm),  $L$  ( $\text{J s}^{-1} \text{Hz}^{-1}$ ), and the stellar rotational velocity,  $v_{\text{rot}}$  ( $\text{km s}^{-1}$ ) given by  $\log_{10}[L/(R_{\star}/R_{\odot})^{2.5}] = 5.0 + (2.5 \pm 0.5) \log_{10} v_{\text{rot}}$ . The correlation, extending over  $v_{\text{rot}} = 1 - 100 \text{ km s}^{-1}$ , can be explained by gyrosynchrotron radiation from coronal structures, in which the fraction of the stellar surface and corona occupied by intense magnetic fields increase with rotation velocity.

*RS CVn binaries:* in RS CVn binaries, quiescent and flaring gyro-synchrotron radio emission is generated from MeV electrons in magnetic structures related to the intra-stellar region and stellar photosphere respectively. For the close binary  $\sigma^2$  CrB, observations since 1987 yielded post-fit rms residuals of 0.20 mas (Lestrade et al., 1996, 1999). This corresponds, at  $d = 21$  pc, to the displacement expected for a Jupiter-like planet around the binary system. No residuals attributable to other orbiting planets were apparent.

*M dwarfs:* the discovery of radio emission from late-M and L dwarfs (Berger et al., 2001; Berger, 2006) provides the possibility of detecting exoplanet or brown dwarf companions to stars and brown dwarfs with  $M < 0.1 M_{\odot}$ . Radio emission in late-type stars originates from cyclotron radiation due to non-relativistic electrons in the coronal plasma, and M dwarfs are sufficiently bright and numerous for large-scale astrometric exoplanet searches to be undertaken.

Very long baseline interferometry (VLBI), with baselines of several thousand km combined with phase referencing techniques, is required to achieve such sub-mas accuracies (Bower et al., 2009; Forbrich & Berger, 2009). The Very Long Baseline Array (VLBA), operational since 1993 and baselines up to 8000 km, achieves astrometric accuracies of  $\sim 100 \mu\text{as}$  at a single epoch at  $\nu < 10$  GHz, and  $\sim 20 \mu\text{as}$  at higher frequencies (Pradel et al., 2006; Reid, 2008), and as high as  $8 \mu\text{as}$  under favourable circumstances (Fomalont & Kopeikin, 2003). The European VLBI Network (EVN), formed in 1980, achieves comparable performances. Multi-epoch measurements yield parallaxes for Galactic sources with  $10 \mu\text{as}$  accuracy, with proper motions of galaxies being determined to  $\sim 1 \mu\text{as yr}^{-1}$  (Reid & Honma, 2014).

Targets for VLBI must have high brightness temperatures,  $T_{\text{b}} > 10^7 - 10^8$  K, to be detectable. This precludes sources of thermal emission at the longest baselines, and requires significant non-thermal flux to achieve the highest astrometric accuracies. Non-thermal radio emission has been detected from various stellar types (Güdel, 2002), including brown dwarfs (Berger, 2006), proto-stars (Bower et al., 2003), massive stars with winds (Dougherty et al., 2005), late-type stars (Gary & Linsky, 1981), and close binaries including RS CVn-type, Algol-type, and X-ray binaries (box, page 101).

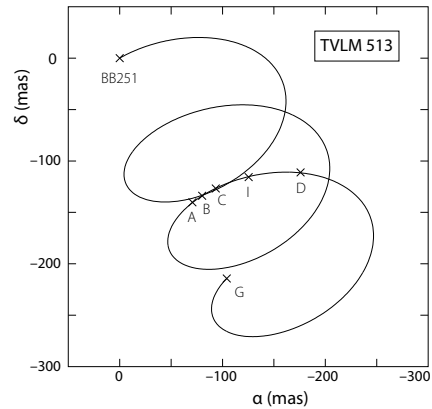


Figure 3.10: NRAO VLBI observations over three years for the M8.5 dwarf TVLM 513, illustrating the state-of-the-art of exoplanet astrometry with radio interferometry. Crosses show the 7 observation epochs, including that of Forbrich & Berger (2009, BB251). The curve is the 5-parameter fit to position, proper motion and parallax (positional uncertainties are not visible at this scale). The absence of residual motion leads to constraints on the companion mass and orbital period. From Forbrich et al. (2013, Figure 2), by permission of IOP Publishing/AAS.

**M dwarf surveys** Bower et al. (2009) surveyed 172 active M dwarfs within 10 pc with the VLA, detecting 29 above  $100 \mu\text{Jy}$ . Seven were then observed with the VLBA. With a detection threshold of  $500 \mu\text{Jy}$ , four were detected at just two or three epochs. Although insufficient for detecting (barycentric) planetary perturbations directly, residuals from the optically determined motions were used to exclude companions with  $M_{\text{p}} \sim 3 - 6 M_{\text{J}}$  at  $a \sim 1$  au.

VLBI detection of the M8.5 dwarf TVLM 513-46546 (Forbrich & Berger, 2009) led to an astrometric search for a substellar companion using long-term observations NRAO Very Long Baseline Array (VLBA). From the absence of residual motion over 3 yr (Figure 3.10), Forbrich et al. (2013) excluded a phase space of companion masses and orbital periods ranging from  $[3.8 M_{\text{J}}, a \sim 0.05 \text{ au}]$  to  $[0.3 M_{\text{J}}, a \sim 0.7 \text{ au}]$ . Their measured (absolute) parallax,  $\varpi = 92.92 \pm 0.23$  mas, corresponds to  $d = 10.762 \pm 0.027$  pc.

The Radio Interferometric Planet search is a follow-up on 30 M stars using the VLBA and the 100-m Green Bank Telescope. With 12 observations over 4-yr per star, and an accuracy of  $\sim 100 \mu\text{as}$  per epoch, the goal is to detect  $1 M_{\text{J}}$  planets at 1 au. For GJ 896A, upper limits are  $0.15 M_{\text{J}}$  at 2 au (Bower et al., 2011).

### 3.11.2 Astrometry at mm/sub-mm wavelengths

Analogous to astrometric searches in the optical, the possibility of indirectly detecting exoplanets based on the astrometric displacement of the thermal emission from the stellar photosphere has also been considered (Lestrade, 2003, 2008). For ALMA (§7.12.2), operation at 345 GHz optimises the combination of detector noise, object spectrum, and site characteristics, and yields a theoretical precision of order 0.1 mas. This corresponds to a minimum planetary mass of  $0.1 M_{\text{J}}$  which could be established astrometrically for some 400 nearby stars.



# Timing

**A**N ORBITING PLANET IS ACCOMPANIED by the periodic oscillation of the position of the host star about the system barycentre, recognisable through changes in the radial velocity and astrometric position of the primary.

If a planet host also possesses some periodic time signature, then these can provide an alternative route to the dynamical detection of orbiting planets through the change in measured period due to light travel time. This has an amplitude related to the displacement of the host (star or star system) along the line-of-sight

$$\tau_p = \frac{1}{c} \frac{a \sin i M_p}{M_\star}, \quad (4.1)$$

where  $c$  is the velocity of light.

As of the end of 2017, some 20 planets (including 3 multiple systems) have been discovered by timing techniques (Table 4.1), in addition to those discovered or confirmed via transit timing variations (Chapter 6).

## 4.1 Candidates and time scales

There are three classes of object, in addition to transiting planets, which offer this measurement possibility: radio pulsars, pulsating stars, and eclipsing binaries (some themselves comprising pulsating stars).

The inherent complexity in the practical implementation of time referencing offers numerous pitfalls in the timing of astrophysical phenomena at the levels of seconds or even minutes, especially evident when dealing with multi-site or multi-instrument efforts. While the pulsar community has faced and mastered these issues over several decades, the problem is a relatively new challenge for exoplanet research.

A further complication is that the commonly used Julian Date, as well as its heliocentric (referred to the Sun's centre of mass) and barycentric (referred to the solar system barycentre) counterparts can be specified in various time standards (box, page 104). The absence of homogeneity and specificity leaves quoted time stamps ambiguous even at the 1 min level if these are left unspecified or uncorrected.

These ambiguities can then be mistaken for transit timing variations, or can lead to biased eccentricity measurements. For astrophysical events of relevance to exoplanet research, Eastman et al. (2010b) have therefore recommended the consistent use of the Barycentric Julian Date (BJD) in the time scale of Barycentric Dynamical Time (TDB). They advocate that studies should, in addition, specify the site arrival time as a means of 'future-proofing' their adopted transformations.

## 4.2 Pulsars

Pulsars provide short period and extremely stable timing signals, and their careful monitoring led to the first discovery of planetary mass objects around a star other than the Sun, around the 6.2-ms pulsar PSR B1257+12<sup>1</sup>, in 1992. At the end of 2017, the Extrasolar Planets Encyclopaedia listed 13 known planets around 10 pulsars, while the more restricted (in terms of confirmation criteria) NASA Exoplanet Archive listed six planets around four pulsars (Table 4.1). The lowest-mass companion, PSR B1257+12 b, has a mass of  $6.3 \times 10^{-5} M_J \sim 0.02 M_\oplus$ .

### 4.2.1 Characteristics

Pulsars are rapidly spinning highly-magnetised neutron stars, formed during the core collapse of massive stars ( $\sim 8 - 40 M_\odot$ ) in a supernova explosion. They emit narrow beams of radio emission parallel to their magnetic dipole axis, seen as pulses at the object's spin frequency due to a misalignment of the magnetic and spin axes.

There are two broad classes: 'normal' pulsars, typically isolated objects with spin periods  $\sim 1$  s; and msec pulsars, old ( $\sim$ Gyr) neutron stars, spun-up during mass and angular momentum transfer from a binary companion; most known still have (non-accreting) binary companions, either white dwarfs or neutron stars.

<sup>1</sup> Pulsar designations signify the object's right ascension and declination. 'B' indicates pre mid-1990s discoveries in the reference system of equinox and epoch B1950.0. More recent discoveries carry 'J' for the epoch/equinox J2000. Since 1997, this reference system is itself replaced by the ICRS (box, page 86).

**Time scales:** The rate of an atomic clock depends on the gravitational potential and its motion with respect to other clocks; thus the time scale entering the equations of motion depends on the coordinate system to which the equations refer. Since 1984, *The Astronomical Almanac* referred to two such time scales: Terrestrial Dynamical Time (TDT) used for geocentric ephemerides, and Barycentric Dynamical Time (TDB) used for ephemerides referred to the solar system barycentre (Seidelmann, 1992; Seidelmann & Urban, 2010). TDT differs from TAI by a constant offset, which was chosen to give continuity with the former *ephemeris time*. TDB and TDT differ by small periodic terms (arising from the transverse Doppler effect and gravitational redshift experienced by the observer) that depend on the form of the relativistic theory being used: the difference includes an annual sinusoidal term of approximately 1.66 ms amplitude, planetary terms contributing up to about 20  $\mu$ s, and lunar and diurnal terms contributing up to about 2  $\mu$ s.

In 1991 the IAU adopted resolutions introducing new time scales which all have units of measurement consistent with the unit of time, the SI second. Terrestrial Time (TT) is the time reference for apparent geocentric ephemerides, and can be considered as equivalent to TDT. Barycentric Coordinate Time (TCB) is the coordinate time for a coordinate system with origin at the solar system barycentre. Because of relativistic transformations, TDB, and therefore TT, differ in rate from TCB by approximately 49 seconds per century.

The practical realisation of TT is through International Atomic Time (TAI). The basic unit of TAI and TT is the SI second, and the offset between them is conventionally 32.184 s (with deviations, attributable to the physical defects of atomic time standards, probably between the limits  $\pm 10 \mu$ s), so that the realisation of TT in terms of TAI is taken to be  $TT(TAI) = TAI + 32.184$  s.

For civil and legal purposes it is necessary to have a time scale which approximates the diurnal rotation of the Earth relative to the Sun. Historically this has been known as Universal Time, but because the Earth's angular spin rate is variable, the Universal Time scale is non-uniform with respect to TAI. The civil time scale, which has been available through broadcast time signals since 1972, is known as Coordinated Universal Time (UTC), and differs from TAI by an integer number of seconds—it is adjusted, when judged necessary by the International Earth Rotation and Reference Systems Service (IERS, formerly the International Earth Rotation Service), by adding a 'leap' second at midnight on December 31, or on June 30.

The Julian Period is a chronological interval of 7980 years beginning 4713 BCE. It has been used by historians since its introduction in 1583 to convert between different calendars. The Julian Day Number is the integer assigned to a whole solar day in the Julian day count starting from noon GMT, with Julian day number 0 assigned to the day starting at the reference epoch of noon on January 1, 4713 BCE proleptic (backwards extrapolated) Julian calendar. The Julian Date (JD) of any instant is the Julian day number for the preceding noon plus the fraction of the day since that instant. The IAU now recommends that Julian Dates be specified in TT, and that if it is necessary to specify Julian Dates using a different time scale, that the time scale be indicated, such as JD(UT1).

The standard epoch of the fundamental coordinate system J2000 corresponds to JD 2 451 545.0 terrestrial time (TT), and to the calendar date 2000 January 1,  $12^{\text{h}} = 2000$  January 1.5(TT). Epoch definitions are based on the Julian year of 365.25 days. Thus the Julian epoch Jyyyy.yy corresponds to

$$JD = 2\,451\,545.0 + (\text{yyyy.yy} - 2000.0) \times 365.25 \quad (4.2)$$

The Heliocentric Julian Day (HJD) is the same as the Julian day, but adjusted to the frame of reference of the Sun, and thus can differ from the Julian day by up to 498 s (the Sun–Earth light travel time). Ambiguities in its interpretation, with respect to its acceleration, led to the 1991 IAU (Resolution A4) discarding it in favour of Barycentric Julian Date (BJD), referenced to the solar system barycentre.

For practical purposes, Eastman et al. (2010b) set out the terms required to achieve a timing precision ranging from 15 min to 1  $\mu$ s, and provide software tools for the determination of BJD(TDB) to a precision of 1  $\mu$ s for any target observed from Earth or space. The relevant terms are, in decreasing magnitude:

$$\text{BJD(TDB)} = \text{JD(UTC)} + \Delta_{R_{\odot}} + \Delta_{\text{c}} + \Delta_{S_{\odot}} + \Delta_{E_{\odot}}, \quad (4.3)$$

where

JD(UTC) is the Julian Date in UTC;

$\Delta_{R_{\odot}}$  is the Rømer delay, the classical light travel time due to the finite speed of light;

$\Delta_{\text{c}}$  is the clock correction from UTC to TDB, viz. via UTC to TAI, TAI to TT, and TT to TDB;

$\Delta_{S_{\odot}}$  is the Shapiro delay, the general relativistic time dilation for radiation passing near a massive object;

$\Delta_{E_{\odot}}$  is the Einstein delay, the general relativistic effect due to an observer's motion, beyond that of TDB at the geocentre.

While the subscript,  $\odot$ , indicates that the effect is relevant in the propagation of electromagnetic radiation through the solar system, analogous terms may additionally apply within the source system.

Because the reference epoch is so long ago, Julian Dates can be large and cumbersome, and a more recent starting point is frequently used. Of some potential confusion, the Modified Julian Date (MJD = JD – 2 400 000.5) is defined relative to midnight, while the Reduced Julian Date (JD – 2 400 000) is defined relative to noon. For similar reasons, the Kepler mission results (in BJD) are frequently referred to the Barycentric (Kepler) Julian Date, BKJD = BJD – 2 454 833.0 (UTC = 2009 January 1,  $12^{\text{h}}$ ).

In pulsar work, the program TEMPO2 models pulsar arrival times to a precision of  $\sim 1$  ns (Hobbs et al., 2006; Hobbs, 2012). A pulsar-based Ensemble Pulsar Scale (EPS), with a precision comparable to TAI, and offering a new realisation of TT, is under development (Hobbs et al., 2012). Current long-term ( $> 1$  yr) stability is better than  $3.4 \times 10^{-15}$  (Yin et al., 2017).

Table 4.1: Planets discovered from timing signals. Objects are those listed at `exoplanet.eu` on 31 December 2017, ordered (within each type) by discovery date, while ‘\*’ indicates that it is also included in the NASA Exoplanet Archive (the latter listing is more restrictive). Some others have been discovered from Kepler transit time variations (summarised in §4.5, and detailed further in §6.20). Radio pulsars include ablated ‘black widow’ companions, some above the canonical brown dwarf limit. Stellar types are abbreviated: CV (cataclysmic variable), dM (M dwarf), LMXB (low-mass X-ray binary), sdB (subdwarf B), WD (white dwarf).

Name	Type	$V$	$d_*$ (pc)	$M_p$ ( $M_J$ )	$P_{\text{orb}}$ (d)	$a$ (au)	$e$	$M_*$ ( $M_\odot$ )	Discovery reference
Radio pulsars:									
PSR B1957+20 b	pulsar (1.6 ms)	–	1530	22	0.38	0.0002	0.00	1.4	Fruchter et al. (1988)
PSR B1257+12 c (B)	* pulsar (6.2 ms)	–	710	0.013	66.54	0.36	0.02	1.4	Wolszczan & Frail (1992)
PSR B1257+12 d (C)	* "	–	"	0.012	98.21	0.46	0.03	"	"
PSR B1257+12 b (A)	* "	–	"	$7 \times 10^{-5}$	25.26	0.19	0	"	Wolszczan (1994a)
PSR B1620–26 b	* pulsar (11 ms)	24	3800	2.5	36525	23	0	1.4	Thorsett et al. (1993)
PSR J2051–0827 b	pulsar (4.5 ms)	–	1280	28.3	0.10	0.005	0	1.4	Stappers et al. (1996)
PSR J1807–2459 b	pulsar (3.1 ms)	–	2790	9.4	0.07	0.00002	0	1.4	Ransom et al. (2001)
PSR J2241–5236 b	pulsar (2.2 ms)	–	500	12	0.15	0.00005	0	1.4	Keith et al. (2011)
PSR J1719–1438 b	* pulsar (5.7 ms)	–	1200	1	0.09	0.0044	0.06	1.4	Bailes et al. (2011)
PSR B0943+10 b	pulsar	–	–	2.8	730	1.8	0	1.4	Suleymanova & Rodin (2014)
PSR B0943+10 c	"	–	–	2.6	1460	2.9	0	"	"
PSR J0636+5129 b	pulsar (2.9 ms)	–	210	8	0.07	0.00002	0	1.4	Spiewak et al. (2016)
PSR B0329+54 b	pulsar	–	–	0.006	10139	10	0.24	1.4	Starovoit & Rodin (2017)
PSR J2322–2650 b	* pulsar (3.5 ms)	26	230	0.79	0.32	0.01	0	1.4	Spiewak et al. (2018)
Pulsating:									
V391 Peg b	* pulsating (sdB)	14.6	1400	3.2	1170	1.7	0	0.5	Silvotti et al. (2007)
Kepler–429 b <sup>1</sup>	* pulsating (sdB)	16	–	–	0.22	–	–	0.5	Silvotti et al. (2014)
Kepler–429 c <sup>1</sup>	* "	16	–	–	0.33	–	–	"	"
Kepler–429 d <sup>1</sup>	* "	16	–	–	0.81	–	–	"	"
Eclipsing:									
HW Vir (AB) b	eclipsing (sdB+dM)	10.9	181	14.3	4640	4.69	0.4	0.6	Lee et al. (2009)
DP Leo b	* eclipsing (AM Her)	17.5	–	6.05	10230	8.19	0.39	0.7	Qian et al. (2010b)
NN Ser (AB) c	* eclipsing (WD+dM)	16.6	500	6.91	5660	5.38	0	0.7	Beuermann et al. (2010)
NN Ser (AB) d	* "	16.6	"	2.28	2830	3.39	0.2	"	"
HU Aqr (AB) c	eclipsing (CV)	15	–	5.9	5646	6.18	0.29	1	Qian et al. (2011)
UZ For (AB) d <sup>2</sup>	* eclipsing (CV)	18.2	–	7.7	1900	2.8	0.05	0.8	Potter et al. (2011)
NY Vir b <sup>3</sup>	* eclipsing (sdB+dM)	13.3	–	2.78	2987.74	3.39	–	0.6	Qian et al. (2012b)
NY Vir c <sup>3</sup>	"	13.3	–	4.49	9861.75	7.54	–	"	"
RR Cae b	* eclipsing (WD+dM)	14.4	–	4.2	4350	5.3	0	0.6	Qian et al. (2012a)
OY Car b	eclipsing (dwarf nova)	12.2	–	8.48	–	6.18	–	–	Han et al. (2015)
2M J1938+4603 b <sup>4</sup>	* eclipsing (sdB+dM)	–	–	1.9	416	0.92	–	0.6	Baran et al. (2015b)
MXB 1658–298 b	* eclipsing (LMXB)	–	–	23.7	760	1.6	–	–	Jain et al. (2017)

<sup>1</sup> ≡ KIC–10001893, and listed as such in both `exoplanet.eu` and NASA Exoplanet Archive (where method listed as ‘orbital brightness modulation’);

<sup>2</sup> NASA Exoplanet Archive includes UZ For b and c; <sup>3</sup> NASA Exoplanet Archive includes NY Vir b only; <sup>4</sup> ≡ Kepler–451, see notes in Section 4.4.4

Millisecond pulsars are extremely accurate frequency standards, with periods normally changing only through a tiny spin-down at a rate  $\sim 10^{-19} \text{ s s}^{-1}$  due to their low magnetic field strength (Bailes, 1996). Pulse arrival time residuals can be measured with an accuracy of order  $\mu\text{s}$ , with one of the most stable, PSR J0437–4715, showing residuals of 130 ns (van Straten et al., 2001).

The known pulsar population (Table 1.4) exceeds 2600, with more than 80 msec pulsars associated with the Galactic disk, and some 130 in Galactic globular clusters of which Terzan 5 counts 34, and 47 Tuc counts 25. The fastest spin-period is the 716-Hz (1.4-ms) eclipsing binary pulsar PSR J1748–2446ad in Terzan 5. The slowest, PSR J2144–3933, has a period of 8.51 s.

**Effect of orbital motion** The high accuracy of pulsar timing allows low mass bodies orbiting the pulsar to be detected from changes in pulse arrival times. For a circular edge-on orbit of period  $P$ , and assuming a canonical pulsar mass of  $1.35 M_\odot$ , Equation 4.1 can be written in

the form (Wolszczan, 1997)

$$\tau_p \approx 1.2 \left( \frac{M_p}{M_\oplus} \right) \left( \frac{P}{1 \text{ yr}} \right)^{2/3} \text{ ms}. \quad (4.4)$$

Jovian or terrestrial planets should be detectable around ‘normal’ slow pulsars, while substantially lower masses, down to that of the Moon and largest asteroids, could be recognised in millisecond pulsar timing residuals.

Although a few ‘planetary systems’ are now known from precision timing of Galactic msec pulsars, they are not common (Lorimer, 2005). For example, monitoring of 151 young ( $\tau < 2 \text{ Myr}$ ) pulsars for periodicity in pulse arrival time failed to detect any further planetary system candidates (Kerr et al., 2015).

#### 4.2.2 Individual pulsars

The following low-mass companions are listed chronologically by discovery date (see also Table 4.1). As noted in the table, not all are considered planet candidates

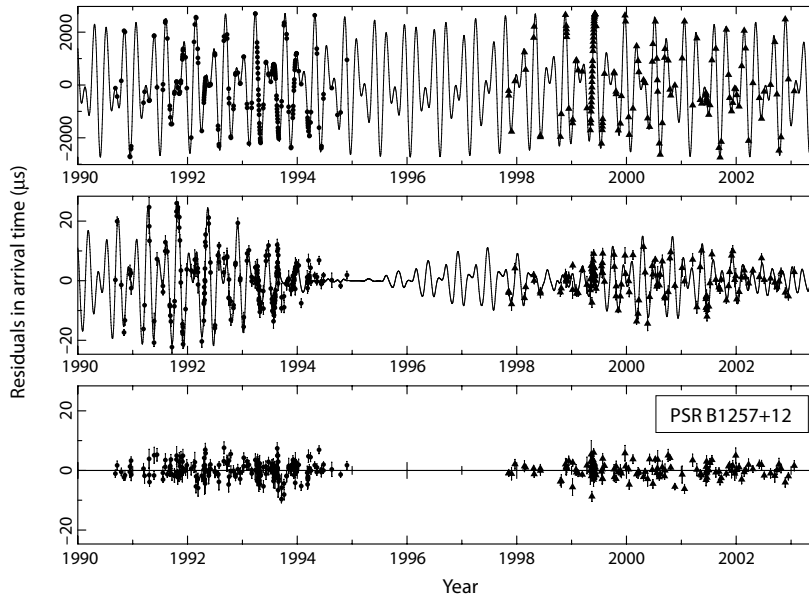


Figure 4.1: Daily-averaged arrival time residuals for PSR B1257+12 observed at 430 MHz with the 305-m Arecibo radio telescope between 1990–2003. Top: residuals for a model without planets. Middle: residuals for a Keplerian model for all three planets, dominated by perturbations between the outer planets. Bottom: residuals after inclusion of planet–planet perturbations. From Konacki & Wolszczan (2003, Figure 1), by permission of IOP Publishing/AAS.

in the NASA Exoplanet Archive. They include ablated companions of the *black widow* class, some above the canonical brown dwarf limit, facilitating comparison with compilations adopting a higher mass cut-off.

While such massive objects are not strictly within the mass limits generally considered for planets, it underlines one of the problems with object classification. If planets are so classified on the basis not only of their mass, but also their formation mechanism, then perhaps none of the known pulsar companions should be considered as ‘planets’. For those pulsar companions resulting from ablation, then an upper mass limit of  $13 - 15M_J$  is, in any case, rather arbitrary.

**PSR B1957+20** Known as the ‘Black Widow Pulsar’, this eclipsing binary system was discovered by Fruchter et al. (1988). The 1.6 msec pulsar is orbited by a companion of mass  $M \sim 22M_J$ , with a period of 9.2 h, and an eclipse duration of  $\sim 20$  min. The comparatively long eclipses are attributed to an extended plasma envelope.

The hypothesis put forward to explain this system is that a once stellar-mass companion to the pulsar is being destroyed via Roche lobe overflow of the neutron star. The ‘black widow’ sobriquet is now applied to the growing class of msec pulsars with an ablating companion (Benvenuto et al., 2012). There is an extensive literature on this object, other members of the ‘black widow’ class, and details of the formation mechanism (e.g. Bednarek & Sitarek, 2013, and references).

**PSR B1257+12** With masses below the canonical brown dwarf limit, the objects orbiting the 6.2-ms pulsar PSR B1257+12 (originally PSR 1257+12) are generally referred to as the first planet-mass objects discovered around an object other than the Sun (Wolszczan & Frail, 1992; Wolszczan, 2012). At least two terrestrial-mass companions were inferred from the timing residuals, with masses of  $M \sin i \simeq 2.8$  and  $3.4 M_\oplus$ . Their orbits were almost circular, with  $a = 0.47$  and  $0.36$  au. Of importance for the subsequent characterisation of the system is the fact that their periods ( $P = 98.22$  and  $66.54$  d respectively) are close to a 3:2 (mean motion) resonance. The original distance estimate from dispersion measures,  $d \sim 300$  pc, is now taken as  $d \sim 700 \pm 40$  pc (Yan et al., 2013, and references). The planets were originally designated PSR 1257+12 A, B and C, ordered by increasing distance. The later convention (followed by CDS SIMBAD and others, that objects are designated by lower-case Roman letters starting from ‘b’, in order of discovery) means that ‘A’ is generally now referred to as ‘b’, ‘B’ as ‘c’, and ‘C’ as ‘d’.

*Confirmation and other planets.* Although a number of alternatives to explain the observed timing residuals were examined (Phillips & Thorsett, 1994), the planet hypothesis could be rigorously verified: the semi-major axes of the orbits are sufficiently similar that the two planets would perturb one another significantly during their orbital close encounters, every  $\simeq 200$  d, with result-

Table 4.2: Orbital and physical parameters of the PSR B1257+12 planets. Planet designations A–C follow those given in Wolszczan (1994a) and Konacki & Wolszczan (2003); designations b–d follow SIMBAD and others (see text).

Parameter	Planet A/b	Planet B/c	Planet C/d
Semi-major axis (ms)	0.0030	1.3106	1.4134
Eccentricity, $e$	0.0	0.0186	0.0252
Orbital period, $P$ (d)	25.262	66.5419	98.2114
Mass ( $M_{\oplus}$ )	0.020	4.3	3.9
Inclination, $i$ ( $^{\circ}$ )	–	53	47
Semi-major axis, $a$ (au)	0.19	0.36	0.46

ing three-body effects leading to departures from a simple non-interacting Keplerian model which would grow with time (Rasio et al., 1992; Malhotra et al., 1992; Malhotra, 1993b; Peale, 1994).

Continued monitoring provided confirmation of the predicted mutual gravitational perturbations, described by osculating terms in which the Keplerian elements evolve with time. Modeling of the orbit evolution allowed masses to be derived without *a priori* knowledge of their orbital inclination,  $\sin i$ . They also provided evidence for a third planet with  $P = 25.34$  d and  $M_{\text{p}} = 0.02M_{\oplus}$ , roughly that of the Moon (Wolszczan, 1994a,b; Konacki et al., 1999b; Wolszczan, 2008).

That the third planet might have been an artefact of temporal changes of heliospheric electron density at the solar rotation rate was discussed (Scherer et al., 1997), but later discounted. Suggestions of a possible fourth planet with  $P \sim 170$  yr (Joshi & Rasio, 1997; Wolszczan, 1997) are unconfirmed.

Konacki & Wolszczan (2003) presented updated results from observations made between 1990–2003 and analysed according to the detailed timing model of Konacki et al. (2000, see Figure 4.1), leading to the physical parameters given in Table 4.2.

*System stability, inclination and co-planarity.* Early dynamical simulations indicated that the orbit configuration of the two outer planets should be stable over some hundreds of thousands of years (Gladman, 1993). This was confirmed by later studies (Konacki & Wolszczan, 2003; Goździewski et al., 2005b; Callegari et al., 2006).

Iorio (2010a) confirmed that Kepler’s third law is an adequate model for the orbital periods of the planets, higher order (Newtonian or general relativistic) corrections being orders of magnitude smaller than their measurement accuracy. Available timing data yields the ratio  $\sin i_{\text{C}} / \sin i_{\text{B}} = 0.92 \pm 0.05$ , independently of the pulsar mass, with co-planarity violating the equivalence principle. For  $1 \lesssim M_{\text{pulsar}} \lesssim 3M_{\odot}$ , both face-on and edge-on orbital configurations for the orbits of the two planets are ruled out; with acceptable inclinations spanning  $36^{\circ} \lesssim i_{\text{B}} \lesssim 66^{\circ}$ , with  $6^{\circ} \lesssim \Delta i_{\text{BC}} \lesssim 13^{\circ}$ .

*Formation.* Early models to explain the existence of planets around pulsars hypothesised three formation mechanisms (Phinney & Hansen, 1993; Podsiadlowski,

1993; Banit et al., 1993; Phillips & Thorsett, 1994). In the first, a planet formed around a normal star, the pulsar progenitor. Its present existence then implies that the planet must have survived the supernova explosion.

A second possibility is that the planet was formed around another star, before being captured by the pulsar through dynamical interaction. A third hypothesis is that the planet was only formed after the supernova explosion which created the neutron star.

In this latter scenario, the supernova would need to retain some residual material that could fall back to form a debris disk around the young neutron star. Subsequent fragmentation would then follow the standard model of planet formation (see also Iorio, 2010b; Yan et al., 2013). Difficulties in modeling planets which survive the supernova explosion may favour the ‘fallback’ accretion disk model, although the rarity of timing companions implies that the process cannot be common.

A model invoking the merger and tidal disruption of a C/O white dwarf by a neutron star binary companion is given by Margalit & Metzger (2017). Rocky planets form rapidly, via gravitational instability, from the debris disk of the disrupted white dwarf, the C/O disk composition likely resulting in C-rich planets with diamond interiors. A quark nova formation scenario is described by Keränen & Ouyed (2003).

*Dust disks.* The simulations of Goździewski et al. (2005b) showed that, for PSR B1257+12, the zone beyond 1 au is also stable, which in turn means that any residual outer dust disk or Kuiper-type belt should also be stable. More direct evidence for the formation and survival of dust disks around neutron stars has also come from the tentative identification of a cool  $10M_{\oplus}$  debris disk around the young X-ray pulsar 4U 0142+61 (Wang et al., 2006).

Foster & Fischer (1996) quantified the observability of a pulsar disk by assuming that a fraction  $f$  of the pulsar spin-down luminosity  $L$  heats  $N$  dust grains of size  $a$  to a temperature  $T$ . The expected infrared flux can then be estimated from  $fL \sim 4\pi a^2 N \sigma T^4$ , along with the pulsar distance estimated from its dispersion measure.

Several attempts to detect dust disks around millisecond pulsars have been made (e.g. Lazio & Fischer, 2004; Löhmer et al., 2004; Wolszczan, 2008). The most stringent limits for PSR B1257+12 come from Spitzer–MIPS observations at 24 and  $70 \mu\text{m}$  (Bryden et al., 2006) which gave limits on a 100–200 K dust disk of below  $3 \times 10^{-5}$  of the pulsar’s spin-down luminosity.

Indirect constraints on the origin of the debris which formed the planets around PSR B1257+12 has come from modeling. Currie & Hansen (2007) showed that a progenitor disk produced by supernova fallback could supply the necessary material. In contrast, tidal disruption of a companion star would underproduce solids within 1 au, while overproducing solids where no body of lunar mass or greater now exists.

The fact that the orbits are nearly co-planar might further support standard models of planet formation. Residual disk material could also have provided the means to circularise the orbits and bring them close to the observed 3:2 resonance (Ruden, 1993).

**PSR B1620–26** Shortly after its discovery, the 11-ms pulsar PSR B1620–26 (in the globular cluster M4) was found to have a binary companion, a  $0.3M_{\odot}$  white dwarf in a 191-d low eccentricity orbit (Lyne et al., 1988; McKenna & Lyne, 1988). Inadequacy of the pulse timing models in predicting the pulsar period and phase at later epochs led to the hypothesis (Backer, 1993) and probable confirmation (Backer et al., 1993; Thorsett et al., 1993) that the observed second period derivative of the pulsar could be attributed to a  $10M_J$  object orbiting the pulsar–white dwarf binary pair. The planetary mass object is the lightest and most distant member of a hierarchical triple system, in an orbit with  $a \sim 35$  au and  $P \sim 100$  yr (Thorsett et al., 1999).

The survival of this outer companion in such a wide orbit in the cluster environment was immediately recognised as problematic because of its low binding energy, and the frequent likely encounters with other cluster stars (Backer et al., 1993). More recent studies of survivability of planets in wide orbits do suggest that such a planet can undergo a number of encounters without unbinding it from the system (Woolfson, 2004).

Data acquired since 2001 with the 100-m Green Bank telescope yield  $M_p \sim 1 - 2M_J$ , with an orbital period of a few decades, a high orbital inclination relative to the plane of the inner pulsar–white dwarf binary, and with modest orbital eccentricity. Signatures of the Newtonian interaction between the planet and the white dwarf are also observed (Sigurdsson et al., 2008).

*Formation.* Three formation scenarios for this hierarchical triple system have been proposed (Figure 4.2). In the first (A; Sigurdsson, 1992, 1993, 1995; Ford et al., 2000a; Sigurdsson et al., 2003, 2008) the planet forms around a main sequence star, then the system migrates towards the cluster core where it encounters a neutron star binary. One neutron star captures the star and planet, and ejects its original companion. The main sequence star then evolves into a red giant (and eventually a white dwarf), transferring mass and so spinning up the neutron star to its final millisecond pulsar status.

A second alternative, also involving exchange (B; Joshi & Rasio, 1997; Fregeau et al., 2006) is that a primordial main sequence planetary system encountered a pre-existing binary millisecond pulsar, in which the planetary system is disrupted, with the main sequence star being ejected and the planet captured.

Since both exchange models require the original planet formation to take place in a (low probability) low-metallicity globular cluster environment, a third possi-

bility (C; Beer et al., 2004b) is that the planet formed by gravitational instability as a passing star perturbed the common-envelope of a main sequence/evolved binary. The main sequence star then transferred mass and spun-up the neutron star to its present ms pulsar status, before evolving to a white dwarf.

With only one exemplar of such a hierarchical triple, and with such a very long period planetary orbit, it is presently difficult to decide between them.

**PSR J2051–0827** A massive companion ( $28M_J$ ) to another black widow 4.5 msec pulsar (see §4.2.2) has been reported orbiting PSR J2051–0827 (Stappers et al., 1996, 1998, 1999, 2000, 2001a,b; Doroshenko et al., 2001; Lazaridis et al., 2011; Wu et al., 2012).

**PSR J1807–2459** Ransom et al. (2001) discovered the 3.06-ms binary pulsar PSR J1807–2459 in the globular cluster NGC 6544. It has an implied companion mass of  $\sim 10M_J$ ,  $P_{\text{orb}} \sim 1.7$ -hr and, like other black widow pulsars, eclipses attributed to their companion winds.

**PSR J2241–5236** PSR J2241–5236 is a 2.2-msec binary, also of the black widow class, with a 3.5-h orbital period, and a companion mass of  $\sim 12M_J$  (Keith et al., 2011).

**PSR J1719–1438** PSR J1719–1438 (Bailes et al., 2011; van Haften et al., 2012) is a 5.7-ms pulsar from the Parkes 64-m High Time Resolution Universe Pulsar Survey (Keith et al., 2010). It is in a binary system with  $P \sim 2.2$  h, and companion mass  $\sim 1M_J$ . Its minimum inferred density,  $23 \text{ Mg m}^{-3}$ , suggests that it may be an ultra low-mass carbon white dwarf. Like others of the black widow class, the system is presumed to have been an ultra-compact low-mass X-ray binary, where the companion has (so far) avoided complete destruction (Benvenuto et al., 2012; van Haften et al., 2012). Referred to as the ‘diamond planet’, the companion’s carbon composition and pressure make it likely to be crystalline, or perhaps some other exotic (quark) matter (Benvenuto et al., 2012; Huang & Yu, 2017).

**PSR B0943+10** This candidate 2-planet system was discovered with the Large Phased Array of the Pushchino Radio Astronomy Observatory. Timing observations were conducted during 2007–2013 (Suleymanova & Rodin, 2014; Suleymanova & Pugachev, 2017).

**PSR J0636+5129** PSR J0636+5129 is a 2.9-ms pulsar with a low-mass ( $8M_J$ ) companion in a 96-minute orbit discovered in the Green Bank North Celestial Cap pulsar survey (GBNCC Stovall et al., 2014), characterised from X-ray observations with XMM–Newton (Spiewak et al., 2016). The companion is similar to the ‘diamond planet’ around PSR J1719–1438, suggesting that it will evolve into an isolated millisecond pulsar following a period of mass-transfer in an ultra-compact X-ray binary.



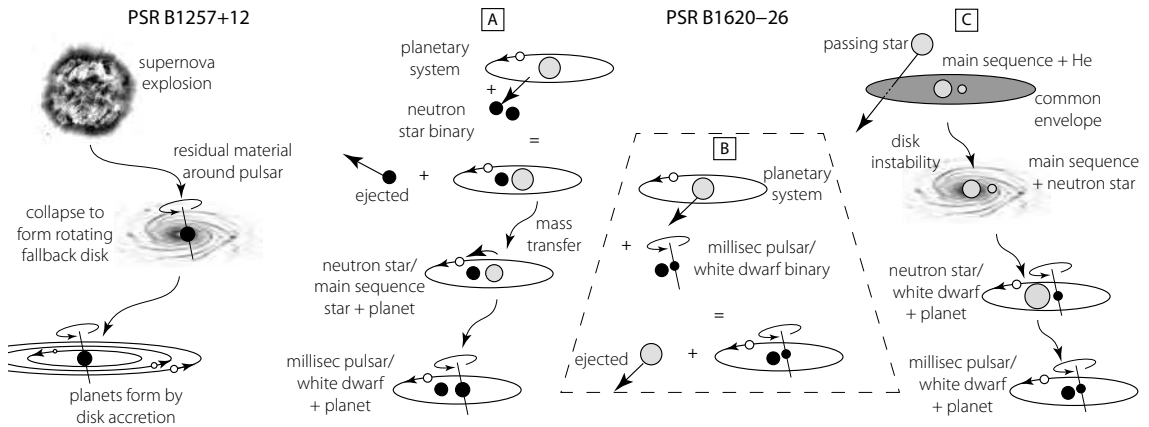


Figure 4.2: Schematic of the formation of the pulsar planets. Left: for PSR B1257+12, the planet is surmised to have formed from a ‘fallback disk’ created after the supernova explosion. For PSR B1620–26, three options are described in the text. A and B involve different capture-and-exchange scenarios of a pre-existing main sequence star–planet system, while C involves planet formation via disk instability after a passing star disrupts the common envelope of a main sequence/giant binary.

**PSR B0329+54** The planet candidate around the slow 0.71-s pulsar PSR B0329+54 has a long history and still uncertain status. Discovered in 1968, evidence for a  $P = 3$  yr planet was reported by Demianski & Proszynski (1979). The planet interpretation was not confirmed by Cordes & Downs (1985), but the periodicity was confirmed with data from the 76-m Jodrell Bank telescope (Bailes et al., 1993). It was also confirmed with data from the Pushchino observatory (Shabanova, 1995), who gave  $P = 16.9$  yr,  $M_p > 2 M_\oplus$ ,  $e = 0.23$  and  $a = 7.3$  au. Both groups reported an additional 3 yr periodicity. With further observations, including the 100-m Effelsberg and 32-m Torun telescopes, timing residuals were attributed to spin irregularities, spin axis precession, or pulsar timing noise (Konacki et al., 1999a; Hobbs et al., 2010; Shabanova et al., 2013).

Analysis of almost 50 years of timing observations (1968–2012) from the Pushchino observatory, the JPL DSN telescopes, and the Kalyazin 64-m telescope again suggest periodic barycentric timing residuals, and a planet with  $P = 27.8$  yr,  $M_p \sin i = 2 M_\oplus$ , and  $a = 10.26$  au (Starovoit & Rodin, 2017).

**PSR J2322–2650** PSR J2322–2650 is a 3.5-ms pulsar found in the southern section of the High Time Resolution Universe survey with a  $0.79 M_J$  companion in a 7.75-h circular orbit (Spiewak et al., 2018). A source of  $R \sim 26.4$  mag was found with the Keck telescope.

#### 4.2.3 Other considerations

**Rarity of pulsar planets** Martin et al. (2016a) have argued that the rarity of pulsar planets is due mainly to two effects. Given that the most likely formation mechanism requires the destruction of a companion star, only pulsars with a suitable

companion (with an extreme mass ratio) are able to form planets. Furthermore, while a (low turbulence) dead zone in the disk is generally thought to be essential for planet formation, it is most probably rare in disks around pulsars, in which intense irradiation from the pulsar strongly heats the inner parts of the disk, pushing the inner boundary of the dead zone outward.

**False alarms and unconfirmed planets** Before the announcement of PSR B1275+12 in 1992, there had been a number of pulsar–planet claims, generally considered as false alarms. The first of these, PSR B0329+54, has an involved history, summarised above.

For PSR B1829–10, Bailes et al. (1991) announced a possible  $10 M_\oplus$  companion, later retracted (Lyne & Bailes, 1992).

For the radio quiet pulsar Geminga, Mattox et al. (1998) reported evidence for a companion ( $a = 3.3$  au,  $M_p \sin i = 1.7 M_\oplus$ ) from  $\gamma$  ray observations, possibly a spin period artefact.

**Satellites of pulsar planets** In the same way that transit time variations for transiting planets can be used to place constraints on the presence of planetary satellites (§6.22.1), pulsar arrival time residuals can be similarly analysed. Lewis et al. (2008) considered systems in which the satellite–planet and planet–pulsar orbits are circular and co-planar (cf. the study of radial velocity variations of a binary star on a distant companion by Schneider & Cabrera 2006), and showed that plausible configurations with detectable signals might exist in PSR B1620–26.

**Detection limits** Detection limits for planets or satellites through arrival time analyses are affected by their own statistical noise properties governing ‘clock purity’ (Cordes, 1993), notably phase jitter due to pulse-to-pulse profile variations, and red timing noise in which neighbouring residuals are correlated, attributed to inhomogeneous angular momentum transport. Other limits may arise from planet–planet interactions in the same system (cf. Laughlin & Chambers, 2001), pulsar precession (e.g. Stairs et al., 2000; Akgün et al., 2006; Haberl et al., 2006; Liu et al., 2007a), periodic structural variations in the interstellar medium (Scherer et al., 1997; You et al., 2007), and stochastic gravitational wave background (e.g. Detweiler, 1979; Hobbs et al., 2009; Pshirkov et al., 2010).

**Interaction of planets with the pulsar wind** Electromagnetic interaction between the relativistic pulsar wind and an orbiting ‘planet’ has little effect on orbits around msec pulsars, but over millions of years can alter the orbit of 10–100 km sized objects around pulsars with spin periods of order 1 s, and magnetic fields of order  $10^8$  T (Mottez & Heyvaerts, 2011b,a). Planetary composition could be probed using radio line spectroscopy to detect molecular absorption lines before and after the total eclipse (Ray & Loeb, 2017).

**Exotic composition** For PSR B1828–11, Liu et al. (2007a) attributed correlated periodic variations in pulse shape and slow-down rate to forced precession by a quark composition planet. Quark composition was also noted as an explanation for the absence of pulse arrival time modulations, even for an edge-on orbit, in the case of PSR J1719–1438 (Benvenuto et al., 2012; Huang & Yu, 2017).

**Pulsar planet habitability** Planet habitability has been considered, and not precluded in the case of the two super-Earths orbiting PSR B1257+12, by Patruno & Kama (2017).

**Solar system masses** Masses of the solar system planets can be constrained by pulsar timing (Hobbs, 2013; Verbiest et al., 2016), providing an alternative to estimates from spacecraft flybys. Since a solar system ephemeris (prescribing the location of masses as a function of time) is required to convert pulse arrival times to the solar system barycentre, an error in planet mass leads to a sinusoidal variation in the inferred pulse arrival times. In principle, the mass distribution in the outer parts of the solar system can be similarly constrained.

Champion et al. (2010) used four pulsars to determine masses from Mercury to Saturn. Their results were consistent with masses determined from spacecraft observations, with the mass of the Jovian system,  $9.547921(2) \times 10^{-4} M_{\odot}$ , being more accurate than determined from Pioneer and Voyager, and consistent with but less accurate than the value from Galileo.

## 4.3 Pulsating stars

### 4.3.1 Context

A planet orbiting a pulsating star will result in a changing apparent stellar pulsation period around the orbit, due to light travel time, in the same way as for the modulation of a pulsar’s observed spin rate.

The realisation that planets could exist around stars in their final evolutionary stages (box, page 113) has led to numerous searches around (pulsating) white dwarfs, and around extreme horizontal branch (sdB) stars.

The existence of planetary systems around stars in such advanced stages of stellar evolution is of interest for two reasons. If survivability is robust, it would provide another route to characterising their frequency and distribution. At the same time, these studies are providing an insight into the future of the solar system planets in general, and of the Earth in particular.

With few planets known around stars in the late stages of stellar evolution, survivability beyond the main sequence is currently a topic somewhat restricted to theoretical investigation (Livio & Soker, 1984; Sackmann et al., 1993; Soker, 1994, 1996; Duncan & Lissauer, 1998;

Soker, 1999; Debes & Sigurdsson, 2002; Burleigh et al., 2002; Hansen, 2004; Villaver & Livio, 2007).

At the same time, some of the scenarios investigated have observable consequences: in tracing the evolution of Jupiter’s orbit as the Sun evolves to form a planetary nebula, Soker (1994) found that Jupiter is likely to deposit a substantial fraction of its orbital angular momentum in spinning-up the Sun, leading to a degree of axisymmetric mass loss from the Sun, and resulting in an elliptical planetary nebula. The observed fraction of elliptical planetary nebulae may therefore correlate with the distribution of massive planets and brown dwarfs.

### 4.3.2 White dwarfs

Various programmes are attempting to quantify the occurrence of planets around white dwarfs. They follow two principal observational routes: the detection of pulsation-timing signatures (considered here), and through direct imaging (§7.10). More general considerations of white dwarfs, the possible survival or existence of planets around them, and the results of imaging and other searches, are given in Section 8.9.

**Pulsating white dwarfs** As a white dwarf cools through certain temperature ranges, C/O (at  $\sim 10^5$  K), He (at  $\sim 2.5 \times 10^4$  K) and H (at  $\sim 10^4$  K) in its photosphere progressively become partially ionised, driving multi-periodic non-radial *g*-mode pulsations. These pulsating white dwarfs are classified as GW Vir, DBV, and DAV (or ZZ Ceti) stars respectively. They have pulsation periods in the range 100–1000 s.

They include some of the most stable pulsators known, both in amplitude and phase. As a consequence, timing methods similar to those used to search for orbiting planets around radio pulsars can be applied.

Currently, several candidates been identified, but none have been unambiguously confirmed.

**G117–B15A** The pulsation period of the  $V = 15.5$  mag DAV white dwarf G117–B15A is  $P \approx 215.197$  s. Data extending back to 1975 were originally acquired as a probe of white dwarf interiors (Kepler et al., 1991, 2000). Observations between 1975–2005 give a period derivative  $\dot{P} = (3.57 \pm 0.82) \times 10^{-15} \text{ s s}^{-1}$  (Kepler et al., 2005). Measuring clock stability by  $P/\dot{P}$ , the stability of G117–B15A is comparable to that of the most stable ms pulsars having  $\dot{P} = 10^{-20} \text{ s s}^{-1}$ .

Similar to the timing of the pulsar planets, the effects of an orbiting planet would result in a periodic change in the measured pulse arrival time with an amplitude given by Equation 4.1. As for the astrometric signature to which this timing amplitude is related, the signal increases with both  $a$  and  $M_p$ . No periodicity in the pulse arrival time residuals has been observed, which excludes the existence of planets around G117–B15A with masses

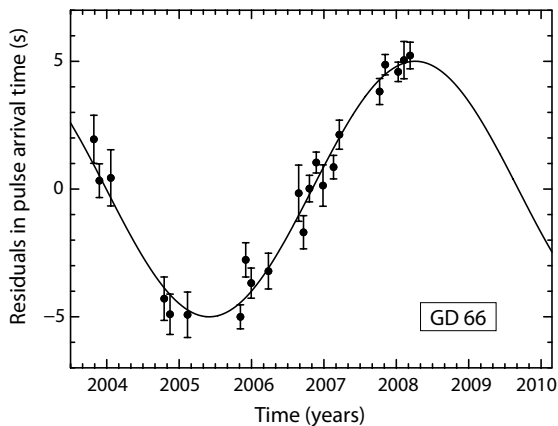


Figure 4.3: Residuals in pulse arrival time for the 302-s mode of the white dwarf GD 66. The timing residuals are consistent with a  $2M_J$  planet in a 4.5-yr orbit. From Mullally et al. (2009, Figure 5, itself updated from Mullally et al. 2008, Figure 2), by permission of IOP Publishing/AAS.

$\sim 0.1 - 10M_J$  and orbital radii in the range 10–0.1 au respectively (Kepler et al., 2005, their figure 4).

A planet with an orbital period much longer than the observational baseline could still give rise to an apparently linear change in pulsation period,  $\dot{P}$ , given by (Kepler et al., 1991)

$$\dot{P} = \frac{P}{c} \frac{GM_p \sin i}{a^2}, \quad (4.5)$$

where  $P$  is the white dwarf pulsation period. The question is then whether the observed period derivative is the consequence of a very long orbital period companion, or has some other origin.

Three other possibilities have been considered (Kepler et al., 2005). The first arises from the white dwarf cooling, estimated to result in  $\dot{P} \approx 10^{-15} \text{ s s}^{-1}$ . A second contribution, estimated at  $\dot{P} \leq 3.8 \times 10^{-15} \text{ s s}^{-1}$ , could arise from a known wide-separation proper motion companion to the white dwarf which may or may not be in orbit around it. A third arises from the star's radial velocity and proper motion (Pajdosz, 1995; Kepler et al., 2000). If all of these possibilities could be excluded, the observed period change could signal a planet with  $M_p \approx 1M_J$  at  $a \approx 30 \text{ au}$  ( $P \approx 200 \text{ yr}$ ), or a smaller planet in a correspondingly closer orbit.

**G29–38** G29–38 is another very stable white dwarf pulsator for which there have been various claims for companions. All of these were shown to be spurious by more careful long-term pulsation timing (Kleinman et al., 1994; Provencal, 1997). The combination of timing studies, 2MASS photometry, and high contrast imaging using HST and Gemini places limits on the existence of any planet at below  $12M_J$  for separations between 1–5 au and ages between 1–3 Gyr (Debes et al., 2005a).

**GD 66** Mullally et al. (2008) monitored 15 white dwarfs for planetary timing signatures. Twelve have been observed since 2003 with the McDonald 2.1-m telescope, with a further three (including G117–B15A) included in longer-term campaigns. While for most objects, companion masses down to a few  $M_J$  at 5 au can be excluded, one star, GD 66, shows a variation in arrival time consistent with a possible  $2M_J$  planet in a 4.5 yr orbit (Figure 4.3). Imaging with Spitzer–IRAC currently place an upper limit on its mass of 5– $7M_J$  for an assumed age of 1.2–1.7 Gyr (Mullally et al., 2009), with comparable limits from HST–FGS astrometry (Farihi et al., 2012c).

#### 4.3.3 Rapidly pulsating subdwarfs

Hot subdwarfs, of spectral types O and B, also termed *extreme horizontal branch stars*, represent a rare late evolutionary stage for some solar mass stars. Some 1% undergo a catastrophic mass loss near the tip of the red giant branch, losing almost all of their hydrogen-rich envelope in an outflowing wind, and resulting in a dense, core He-burning, O- or B-type subdwarf, characterised by an extremely thin H envelope, and with  $T_{\text{eff}} \sim 30000 \text{ K}$  (Kilkenny, 2007; Heber, 2009; Østensen, 2009). A subset show short-period  $p$ -mode pulsations, which can be used as the reference timing signature.

Assuming their survival through the common envelope phase (box, page 113), Bear & Soker (2011b) found that Jupiter-like planets orbiting within  $10R_{\odot}$  will undergo non-negligible mass loss during their  $10^8 \text{ yr}$  lifetime on the horizontal branch. With ionisation of the evaporated gas, detection could be possible via the periodic variation of the Doppler shift of the Balmer lines.

While half of sdB stars are in binary systems and their formation can be explained by binary evolution (Han et al., 2002, 2003; Bear & Soker, 2011a), explaining the formation of (apparently) single sdBs poses more of a problem. It has been suggested that a planet of sufficient mass ( $\gtrsim 10M_J$ ), and sufficiently close to the star, may have enough energy and angular momentum to remove the red giant envelope and trigger formation of an sdB star (Soker, 1998). Opposing effects of stellar mass loss (causing an outward planet drift), and tidal forces (causing an inward drift), may create a gap in a certain range of orbital distances (Nordhaus et al., 2010).

There are a number of sdB stars (mainly single) that show some evidence of substellar companions. They belong to three different groups, distinct in terms of orbital distance and planetary mass. In order of increasing orbital distance, there are at least five close brown dwarf candidates with  $P \lesssim 1 \text{ d}$ , discovered from radial velocity measurements (Geier et al., 2012); two Earth-mass planet candidates around the sdB pulsator Kepler–70 (KIC–5807616), with orbital periods of 5.8 and 8.2 h, and discovered by transit photometry (Charpinet et al., 2011; Bear & Soker, 2012), and a number of planet/brown

dwarf candidates with masses between  $2-40M_J$  in large orbits with orbital periods between 3.2–16 yr, discovered from timing studies, and detailed below.

Amongst timing programmes, the EXOTIME project (EXOplanet search with the TIming MEthod) is monitoring five targets over several years (V391 Peg, QQ Vir, V541 Hya, V1636 Ori, DW Lyn), focusing on large orbits around single stars not part of known binary systems (Schuh et al., 2010; Lutz et al., 2012; Schuh et al., 2014).

**V391 Peg** Silvotti et al. (2007) reported the discovery of a  $M_p \sin i = 3.2M_J$  planet orbiting the sdB-type star V391 Peg, with  $a = 1.7$  au and  $P = 3.2$ -yr.

Like some 40 others of its class, V391 Peg shows stable  $p$ -mode pulsations (Kilkenny, 2007; Lutz et al., 2009), with four or five periods between 342–354 s. Superimposed on a change of the main period at a rate of  $\dot{P} = (1.46 \pm 0.07) \times 10^{-12} \text{ s s}^{-1}$  is a 3.2-yr periodicity, seen in both the main and second pulsation frequencies (Figure 4.4), and taken as signatures of an orbiting planet.

Probably with  $a \approx 1$  au when on the main sequence, the planet would have moved outwards adiabatically to its present position as the star lost mass. Unlike planets surrounding white dwarfs, evolution to the present location has only been affected by the red giant phase (and not the asymptotic giant branch and thermal pulses). As noted for some sdB stars more generally, a possible causal link between the suggested planet and the extreme mass loss, which led to these pulsating hot subdwarf, is detailed by Soker (1998).

More recent data over a 13-yr period does weaken the orbiting planet hypothesis (Silvotti et al., 2018).

**Kepler-429** Kepler-429 (KIC-10001893 in the NASA Exoplanet Archive, and classified there as discovered through ‘orbital brightness modulation’, §6.15, rather than through timing) is one of 19 sdB pulsators observed by Kepler during its primary mission. In addition to tens of  $g$ -mode pulsation frequencies, its Fourier spectrum shows three weak peaks at very low frequencies, too low to be considered as  $g$  modes. Silvotti et al. (2014) attribute these to the orbital modulation of three Earth-size planets (or planetary remnants) in very tight orbits, which are illuminated by the strong stellar radiation. The orbital periods, of 5.273, 7.807, and 19.48 h, are very close to 3:2 and 5:2 mean motion resonances.

One of the main stellar pulsation modes at  $210.68 \mu\text{Hz}$  corresponds to the third harmonic of the orbital frequency of the inner planet, suggesting that these  $g$ -mode pulsations are tidally excited by the planet. This extreme planetary system is very similar to the two Earth-size planets orbiting the sdB pulsator Kepler-70 (KIC-05807616; Charpinet et al., 2011).

**Unconfirmed candidates** Amongst unconfirmed candidates are V1636 Ori (Schuh et al., 2014) and DW Lyn (Schuh et al., 2014).

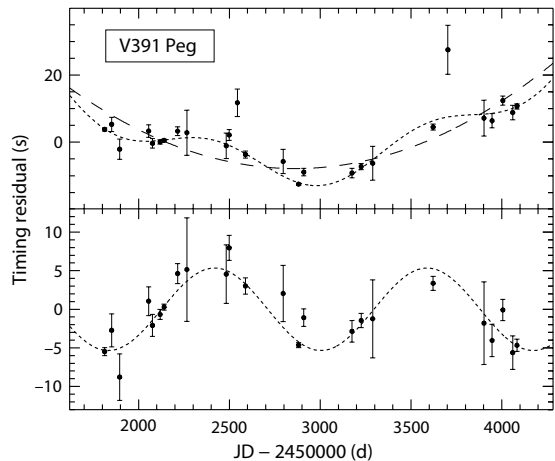


Figure 4.4: V391 Peg, showing residuals in the pulse arrival times for the main pulsation frequency over six years. Models are for a linear period derivative (top figure, dashed curve), and one including an additional sinusoidal component with  $P = 3.2$  yr (top figure, dotted). Only the sinusoidal component is shown below. From Silvotti et al. (2007, Figure 1), by permission from Nature/Springer/Macmillan Ltd, ©2007.

## 4.4 Eclipsing binaries

### 4.4.1 Context

Circumbinary planets (§10.12) have been detected through their radial velocity signatures (§2.13), and through transit photometry (§6.3). In addition, a planet orbiting both components of an eclipsing binary will result in periodically varying eclipse times as the binary itself circles the combined system barycentre. With timing accuracies of about 10 s for selected eclipsing binaries showing sharp eclipses, it should be possible (according to Equation 4.4) to detect circumbinary planets of  $\sim 10M_J$  in 10–20 yr orbits. Effects of intrinsic variability (photospheric spots, flares, and pulsations), as well as the noise properties, limit the accuracy of the minima timing. Simulations, sensitivities, and comparison with detection using radial velocities and astrometry, have been reported (Sybilski et al., 2010; Schwarz et al., 2011).

Various searches are being carried out, typically using a network of 0.2–2-m telescopes (e.g. the ‘Dwarf Project’, Pribulla et al., 2012). Typical targets are low-mass eclipsing binaries with M and K components, and close-compact short-period binaries with a white dwarf or hot subdwarf (sdB or sdO, see §4.3.3) component.

Since the amplitude of any timing signal increases with the orbital period of an invisible third component, observations spanning some 5–10 yr are often required.

**Methods** In deriving and analysing eclipse mid-times, a comparison with the trend calculated assuming a constant period, frequently referred to as the observed-minus-calculated (O–C) diagram, is the basic tool for ex-

aming period stability (e.g. Sterken, 2005). As summarised there, the O–C shape can be linear (indicative of a constant but incorrect period), parabolic or irregular (due to evolutionary changes in the system); or sine-like, if caused by companion(s) to a binary system.

Amongst basic procedures, Kwee & van Woerden (1956) detail one method for deriving eclipse mid-times.

**Achievable eclipse timing precision** For favourable systems, with deep primary eclipses, eclipse times with a precisions as low as 0.01 s have been reported (Parsons et al., 2010a). Secondary eclipse timings for NN Ser reach a typical precision of ~4 s, and up to 1.8 s with VLT–ULTRACAM (Parsons et al., 2014).

#### 4.4.2 Candidate systems

**Post-common-envelope binaries** The first substellar circumbinary companion inferred from timing studies is a brown dwarf orbiting the prototype post-common-envelope binary V471 Tau, based on 160 eclipse timings spanning 30 years (Guinan & Ribas, 2001). Discoveries of substellar and mostly planetary mass circumbinary companions have since been claimed for a dozen eclipsing, close-compact binaries containing white dwarf or hot sdB primaries, configurations allowing the eclipse minima to be timed with high precision.

The Sloan Digital Sky Survey and associated follow-up observations, as well as the Catalina Realtime Transient Survey, have significantly increased the number of known eclipsing, detached post-common-envelope binaries (Backhaus et al., 2012). Zorotovic & Schreiber (2013) list 56 detached eclipsing systems, of which 13 comprise an sdB (or sdOB) primary and a main sequence or brown dwarf secondary, while 43 host a white dwarf primary.

Of the 13 comprising an sdB or sdOB primary, a significant fraction, 38%, show apparent period changes that might be caused by a circumbinary companion, while all systems intensively followed up for more than 5 years, with the exception of AA Dor, show such variations (Kilkenny, 2011).

**Cataclysmic variables and polars** Apparent period variations associated with the suggested presence of a third body have also been observed for three cataclysmic variables: DP Leo, HU Aqr, and UZ For.

*Cataclysmic variables* are post-common-envelope binaries comprising an accreting white dwarf and a low-mass ‘donor’ star (usually a red dwarf), that have evolved into a semi-detached configuration, in which the donor overfills its Roche lobe, and so transfers mass onto the white dwarf. Eclipsing cataclysmic variables were discovered more than a century ago, with some 200 eclipsing systems among the 880 listed in the 2010 update of the Ritter–Kolb Catalogue (Ritter & Kolb, 2003, 2010).

**Post-common-envelope binaries:** Giant planets orbiting post-common-envelope binaries are of particularly interest because of the extreme ‘common envelope’ evolutionary phase that the binary passed through to reach its present form (Paczynski, 1976; Webbink, 1984; Zorotovic & Schreiber, 2013). If the initially more massive primary fills its Roche lobe during one of the giant phases, with its deep convective envelope, dynamically unstable mass transfer to the secondary begins, with the secondary unable to adjust its structure on the time scale of the mass transfer. Material lost by the primary initially fills the secondary’s Roche lobe, and then grows to form a non-corotating common envelope that surrounds both the giant core and secondary star, sweeping past any pre-existing planets.

Owing to drag forces within the envelope, orbital energy is extracted from the binary and transferred to the envelope, which dramatically reduces the separation between the core of the primary and the secondary star in a spiraling-in process, until the envelope becomes unbound and is ejected from the binary. The remaining system is a *post-common-envelope binary*, consisting of the core of the primary (a compact object) and a main sequence companion, in a close but detached orbit. The duration of the common envelope phase is very short,  $\leq 10^3$  yr.

Under such circumstances, a circumbinary planet orbiting a post-common-envelope binary must either have formed as a ‘first generation’ object in the protoplanetary disk around the original binary and survived the dramatic evolution of the host binary star, or must have formed as a consequence of it (either as a ‘second generation’ object in a disk formed in the common envelope shed by the primary progenitor, or as a ‘third generation’ object formed from matter lost from the present accreting binary). Which of these takes place is currently an open question, but perhaps with the second-generation scenario being more likely, at least in some cases (e.g. Beuermann et al., 2010; Bear & Soker, 2014; Schleicher & Dreizler, 2014).

Hydrodynamic simulations of common envelope evolution (e.g. Ricker & Taam, 2012) do not yet provide an answer either, because the details of the process are still relatively uncertain, even without an embedded planet.

The subset of cataclysmic variables distinguished by a very strong magnetic field in the white dwarf are referred to as *AM Her stars* or *polars*, the latter a reference to the significantly polarised light that they emit. The strong magnetic field leads to a 1:1 spin–orbit synchronised rotation period of the white dwarf with the orbital period, and to a capturing of the accretion stream from the donor star before it can develop into an accretion disk, resulting in violent shock-driven accretion near one or more of the star’s magnetic poles.

#### 4.4.3 Complicating factors

For the various reasons detailed in the associated studies, the reality of some of the claimed circumbinary giant planets still has to be considered with some caution. Dynamical simulations have indicated that some of the originally claimed planetary orbits are unstable on implausibly short time scales. Contributing to the debate

**Other timing effects:** Inferring the presence of orbiting planets requires the careful control of instrumental effects, including the contribution of ‘red noise’, as well as time scale errors. Orbital period changes may also result from the effects of mass transfer, gravitational radiation, and magnetic breaking (e.g. Rappaport et al., 1983). A variety of other physical phenomena have been described as possibly contributing to changes in eclipse timings:

*Applegate mechanism:* cyclic variation of the binary orbital period can result from the *Applegate mechanism* (Applegate, 1992), in which a magnetic star changes its internal structure throughout its magnetic cycle. This results in a time-varying quadrupole moment  $J_2$  and, consequently, a varying gravitational field for the orbital companion, and hence a varying orbital period (Hilditch 2001; see also Parsons et al. 2010a, eqn 6). The effect has been observed in several cataclysmic variables, including U Gem, which displays a 60 s variation in orbital period over 8 yr (Eason et al., 1983), EX Dra, changing by 1.2 min over 4 yr (Baptista et al., 2000), and EX Hya, modulated on a time scale of  $\sim 17.5$  yr (Hellier & Sproats, 1992). For the systems of relevance here, the effect was discounted as a significant contributor in the case of HU Aqr (Schwarz et al., 2009), although reconsidered by Wittenmyer et al. (2012a), and also explicitly discounted for NN Ser (Brinkworth et al., 2006). The implications for an associated radial velocity ‘jitter’ have been assessed by Cegla et al. (2012).

*Spin and apsidal precession:* long-term periodicities in white dwarf systems have been attributed to the slow precession of a rapidly spinning magnetic white dwarf. This has been proposed to explain long-period changes in a few cataclysmic variables, such as FS Aur (Chavez et al., 2012) and V455 And (Tovmassian et al., 2007). Apsidal motion of the stellar binary can cause large variations in eclipse times, with the amplitude of the shifts proportional to both  $P$  and  $e$ . Eccentricities as low as  $e = 10^{-3}$  can drive deviations in eclipse times of 10 s in a binary with  $P = 3$  h, over time scales from months to decades (Parsons et al., 2014). While such small values of  $e$  are difficult to constrain from radial velocities, apsidal precession can be constrained from *secondary* eclipse timings, i.e. the transit of the compact primary across the face of the M dwarf, because it causes the secondary eclipse to move in the opposite sense to the primary eclipse. However, since the best primary eclipse timing data usually comes from systems with hot white dwarfs (with shallow secondary eclipses), secondary eclipse timings are challenging and possible only in a few cases, such as NN Ser.

*Wilson depression:* the reduced pressure, density and temperature of a star spot results in its depression below the surrounding photosphere by several hundred km, an effect known as the *Wilson effect* or *Wilson depression* (after Alexander Wilson’s interpretation of the structure of the solar limb in 1769). The presence of a Wilson depression on the limb of a secondary star as it occults the primary may cause small changes in mid-eclipse times. With star spot coverage on active stars reaching some 50% or more of the surface (e.g. O’Neal et al., 1998), eclipse timings may be affected by as much as a few seconds (Watson & Dhillon, 2004). The implications for an associated radial velocity ‘jitter’ have been assessed by Cegla et al. (2012).

is the fact that the formation or survival mechanisms for planets accompanying post-common-envelope binary systems remain unclear. Other possible timing complications are noted in the box, page 114.

#### 4.4.4 Individual systems

Eclipsing binary candidates listed in Table 4.1 are described in the same (discovery) order hereafter.

**HW Vir** The very short-period eclipsing binary HW Vir is a  $P_{\text{orb}} = 2.8$  h orbital system, comprising an sdB and a main sequence M star. It is the first eclipsing binary system for which the hypothesis of orbiting planets as an explanation of the eclipse time variations is considered to be reasonably secure. Studied since its discovery in 1980, both Kilkenny et al. (2003) and Ibanoglu et al. (2004) already concluded that the cause of the measured period change was a light travel time effect caused by a third body with  $M \gtrsim 0.02M_{\odot}$  and  $P = 18 - 20$  yr.

Lee et al. (2009) added further observations between 2000–08, and from the timing residuals (Figure 4.5) inferred the presence of two planets, with  $M_p \sin i = 19.2M_J$ ,  $P = 15.8$  yr,  $a = 5.3$  au,  $e = 0.46$  and  $M_p \sin i = 8.5M_J$ ,  $P = 9.1$  yr,  $a = 3.6$  au,  $e = 0.31$  respectively, with a system inclination of  $i \approx 81^\circ$ . The periods suggest 5:3 or 2:1 resonant captures, and the relatively high eccentricities are in line with theoretical results on planet–planet

interaction and stability (Kley et al., 2004; Ford & Rasio, 2008; Pierens & Nelson, 2008a).

Horner et al. (2012a) found that the proposed discovery orbits are dynamically unstable, and derived a new orbital solution providing a very good fit to the observational data but which were, however, also dynamically unstable. Beuermann et al. (2012b) also found the proposed discovery orbits to be unstable, contributed further eclipse times, and presented a new solution stable over  $10^7$  yr with masses  $14M_J$  and  $30 - 120M_J$ , and respective periods  $12.7$  and  $55 \pm 15$  yr.

**DP Leo** DP Leo is a member of the class of AM Her stars or polars, strongly magnetised cataclysmic variables, and the first discovered to be eclipsing. Qian et al. (2010b) showed that a significant sinusoidal light travel time component, with semi-amplitude 31.5 s, can be explained by a  $P = 23.8$ -yr planet ( $a = 8.6$  au) of mass  $6.4M_J$ . This assumes that the planet is co-planar with the eclipsing binary, i.e. with an orbital inclination  $i = 79^\circ.5$ , and that the total binary mass is  $0.69M_{\odot}$ .

New observations and a re-analysis of the existing data by Beuermann et al. (2011) confirmed the planetary nature of the timing signature, and provided revised values of  $P = 28.0 \pm 2.0$  yr,  $a = 8.2 \pm 0.4$  au,  $M \sin i = 6.1 \pm 0.5M_J$  and  $e = 0.39 \pm 0.13$ .

**NN Ser** NN Ser is a  $P = 3.12$ -hr eclipsing binary with a white dwarf primary and red dwarf secondary (Par-

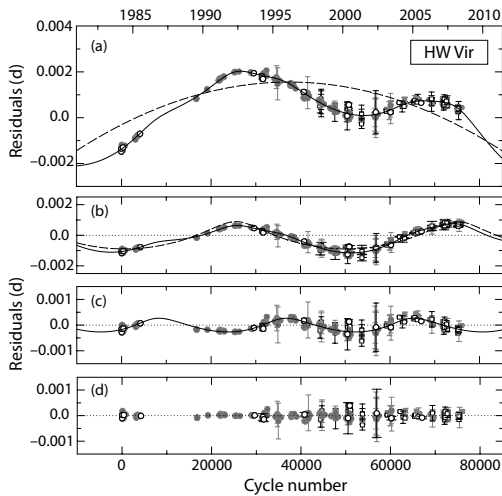


Figure 4.5: *HW Vir*, and the residuals of the eclipse timings measured since the early 1980s with respect to the linear terms of the Ibanoglu et al. (2004) ephemeris: (a) the parabolic curve corresponds to a linear period decrease of  $\dot{P} = -8.3 \times 10^{-9} \text{ d yr}^{-1}$ , which might arise from magnetic stellar wind breaking; (b) residuals from the quadratic form, dependent on  $\dot{P}$ ; (c) residuals after including the effect of the 15.8 yr planet; (d) residuals with respect to the two-planet model. From Lee et al. (2009, Figure 5), by permission of IOP Publishing/AAS.

sons et al., 2010b). Periodic eclipse timing residuals attributed to a  $15M_J$ ,  $P = 7.56\text{-yr}$  planet were first reported by Qian et al. (2009). Observations extending over 22 yr (1988–2010) indicate the presence of two planets, NN Ser (ab) c and d, with masses  $6.9M_J$  and  $2.2M_J$  respectively, periods of 15.5 yr and 7.7 yr, and eccentricities of  $\sim 0$  and  $\sim 0.2$ , in a 2:1 mean motion resonance (Beuermann et al., 2010; Horner et al., 2012b; Beuermann et al., 2013). Commentary on the validity of certain stability analyses are given by Marsh et al. (2014).

Further observation of 25 new eclipse times with WHT-ULTRACAM, Liverpool-RISE, and VLT-HAWK-I, have validated and refined the two-planet model (Marsh et al., 2014), yielding non-zero eccentricities, periods of 7.9 and 15.3 yr, and masses of  $2.3$  and  $7.3M_J$ , in particular correctly predicting a progressive lag in eclipse times of up to 36 s since 2010 (Figure 4.6). They identified consistent and dynamically long-lived orbits associated with 2:1 and 5:2 period ratios.

Apsidal precession as a cause of the observed change in eclipse times (§4.4.3) was excluded by Parsons et al. (2014), who found the same trend in secondary eclipse times as for the primary eclipse. Their data also constrain the eccentricity of the binary to  $e < 10^{-3}$ .

If real, the planets' survival throughout the entire main sequence lifetime of the binary, in particular through the common envelope phase, is generally considered unlikely, with the planets probably being very young objects formed through a second generation

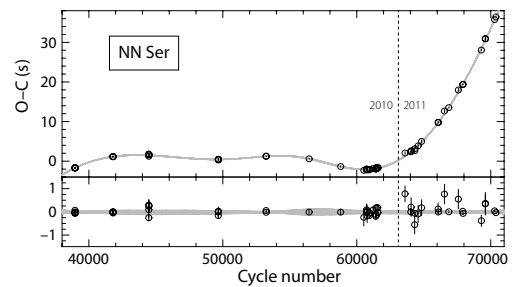


Figure 4.6: 11 yr of eclipse times of NN Ser, starting in 2002 May. Data from before the end of 2010 (dashed line) are from Beuermann et al. (2010). The light-grey smooth curves show 50 two-planet Newtonian orbit fits to the full data set, generated via MCMC iteration. Only data with uncertainties  $< 0.5 \text{ s}$  are shown. Residuals are shown in the lower panel. From Marsh et al. (2014, Figure 3), © Oxford University Press.

process from the fraction of the expelled envelope that remained gravitationally bound to the binary (Mustill et al., 2013; Völschow et al., 2014; Schleicher et al., 2015).

**HU Aqr** Qian et al. (2011) originally reported that precise times of eclipse mid-egress of the eclipsing polar HU Aqr indicated the presence of at least two (and perhaps a third) planets, planet b ( $5.9M_J$ ,  $a = 3.6 \text{ au}$ ,  $P = 6.5 \text{ yr}$ ) and planet c ( $4.5M_J$ ,  $a = 5.4 \text{ au}$ ,  $P = 11.9 \text{ yr}$ ).

Horner et al. (2011) used a dynamical analysis to show that such a system would be highly unstable on time scales of less than 5000 yr, and described a set of modified orbits that would be required for stability. Alternative two planets orbit models were proposed by Wittenmyer et al. (2012a), and independently by Hinse et al. (2012). The possible contribution of the Applegate mechanism (box, page 114) has been variously considered (Schwarz et al., 2009; Wittenmyer et al., 2012a).

New data, and a revised analysis of the existing inhomogeneous observations over 20 years (Goździewski et al., 2012) suggested that the totality of data is best explained by a single circumbinary companion ( $6.7M_J$ ,  $a = 4.3 \text{ au}$ ,  $P = 3278 \text{ d}$ ,  $e = 0.03$ ; their Table 4), as shown in Figure 4.7. Eclipse timings continue to be monitored (Schwope & Thinius, 2014).

Portegies Zwart (2013) showed that the planets allow reconstruction of the binary's evolution through the common-envelope phase. For an isolated binary, there is a degeneracy between the donor mass, its radius, and its core mass. The inner planet allows this degeneracy to be broken, and the outer provides independent validation. Portegies Zwart (2013) found that the common envelope was ejected at a rate of  $1.9M_\odot \text{ yr}^{-1}$ , that the initial binary comprised a  $1.6M_\odot$  primary and a  $0.47M_\odot$  companion with  $a = 97R_\odot$ , and that the two planets were born with semi-major axes  $541R_\odot$  and  $750R_\odot$ .

**UZ For** Eclipse timings for the cataclysmic variable UZ For have been made since very soon after its discov-

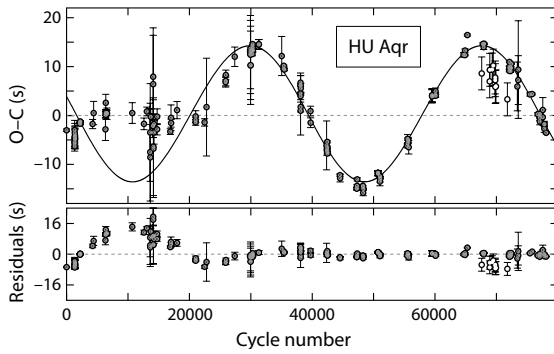


Figure 4.7: The single planet, quadratic ephemeris, light travel time model for HU Aqr from Goździewski et al. (2012), fitted to all available mid-egress times (including the OPTIMA photometer, as well as the PIRATE, TCS and MONET/N telescopes). Open circles are from Qian et al. (2011). The pattern of residuals (lower panel) is attributed partly to an inconsistency in the time standards of the different instruments, with a possible contribution associated with a mass-transfer process related to the binary magnetic cycles. From Goździewski et al. (2012, Figure 8), © Oxford University Press.

ery as an X-ray source in the EXOSAT archive (Giommi et al., 1987). Dai et al. (2010b) drew attention to the possible cyclical change with a period of  $\sim 23$  yr, and attributed it to a probable brown dwarf companion. Potter et al. (2011) obtained high-speed photometry with SALT with the aim of measuring precise mid-eclipse times, with the new and archival data suggesting two cyclic variations at 16 yr and 5.25 yr. They rejected the Aplegate mechanism (box, page 114) as their underlying cause, and favoured instead a two-planet model with minimum masses 6.3 and  $7.7M_J$  respectively.

**NY Vir** Qian et al. (2012b) used new and archival eclipse times to identify a Jovian planet orbiting the rapidly pulsating sdB-type eclipsing binary NY Vir. Cyclic variations with  $P \sim 7.9$  yr and amplitude 6.1 s suggest a circumbinary planet of  $M \sin i = 2.3 \pm 0.3M_J$  orbiting at 3.3 au. An additional parabolic orbital period change,  $\dot{P} = -9.2 \times 10^{-12} \text{ s s}^{-1}$ , too large to be explained by angular momentum loss by gravitational radiation and/or magnetic breaking, suggests a second  $2.5M_J$  planet in a longer period  $\geq 15$ -yr orbit.

Independently, Lee et al. (2014f) used 68 eclipses with timing accuracies better than 10 s to also identify two planetary mass circumbinary bodies, with periods 8.2 and 27 yr, with minimum masses 2.8 and  $4.5M_J$  respectively. Dynamical analysis suggests that the outer companion is on a moderately eccentric orbit. Long-term gravitational attraction may lead to trapping in a 3:10 mean motion resonance.

**RR Cae** Similar to the behaviour of NY Vir, the white dwarf eclipsing binary RR Cae shows a cyclic variation with  $P \sim 11.9$  yr and amplitude 14.3 s, corresponding to

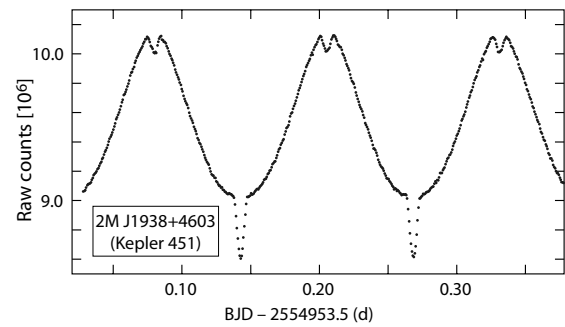


Figure 4.8: Kepler light curve of the 0.126 d sdB + M dwarf binary 2M J1938+4603 (Kepler-451), showing the raw data over an interval of 8 h. The light curve is dominated by reflection effects, with both primary and secondary eclipses also evident. From Østensen et al. (2010, Figure 1), © Oxford University Press.

a  $4.2M_J$  planet orbiting at 5.3 au (Qian et al., 2012a). An additional period increase, i.e. of opposite sign to that expected from magnetic braking or gravitational radiation, suggests a second planet with  $P > 26.3$  yr.

**OY Car** Sinusoidal timing variations were noted for the eclipsing dwarf nova OY Car (Pilarčik et al., 2014). New eclipse times and further analysis by Han et al. (2015) suggests a  $8.5M_J$  planet in a 14-yr orbit.

**2M J1938+4603** 2M J1938+4603 (Kepler-451) is a  $P = 0.126$  d binary system comprising a pulsating sdB star and an M dwarf, identified in the Kepler field during a survey of blue targets selected from 2MASS. Follow-up Kepler photometry revealed a light curve dominated by prominent reflection with shallow, grazing eclipses, both primary and secondary (Figure 4.8). The amplitude spectrum reveals pulsation peaks spanning frequencies from 50–4500  $\mu\text{Hz}$  (Østensen et al., 2010).

Barlow et al. (2012) subsequently derived constraints on the binary component masses and eccentricity, exploiting the classical light travel time (Rømer) delay of the secondary eclipse, using the approach of Kaplan (2010). They derived a delay of  $\sim 2$  s, and a resulting (binary star) mass ratio of 0.2691.

Baran et al. (2015b) analysed 37 months of Kepler photometry, with eclipse timings for 16 000 primary and secondary eclipses revealing a periodic variation in the timing signal of amplitude  $1.27 \pm 0.02$  s. This is attributed to a  $M_P \sin i = 1.9M_J$  planet ( $P = 416$  d,  $a = 0.92$  au), the lowest mass of all tertiary components detected in similar systems to date. The data also show a long-term trend that may be an evolutionary effect, or a hint of other bodies (Figure 4.9).

**MXB 1658–298** Jain et al. (2017) reported X-ray timing analysis of the transient X-ray binary MXB 1658–298 ( $P_{\text{orb}} = 7.1$  h), based on RXTE and XMM–Newton observations during outbursts. The long-term evolution of mid-eclipse times indicates an orbital period decay time scale of  $-6.5 \times 10^7$  yr, with sinusoidal variations (of amplitude of 9 s and  $P \sim 760$  d) attributed to a circumbinary body of inferred mass 20– $25M_J$ .



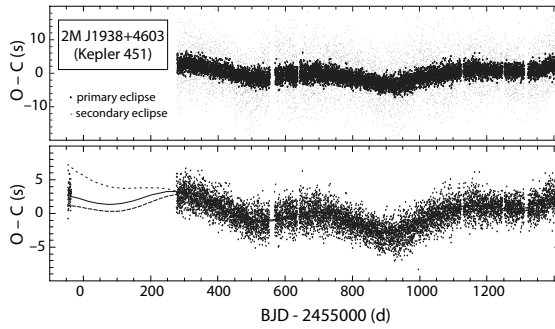


Figure 4.9: Eclipses times over 3 yr for 2M J1938+4603 (Kepler-451) showing (top) the similar patterns of primary and (lower accuracy) secondary eclipses; bottom:  $O-C$  restricted to primary eclipses, with 3 best-fit curves: the adopted  $\text{sine+sine+linear}$  (solid);  $\text{parabola+sine}$  (short dash); and  $\text{sine+sine}$  (long dash). From Baran et al. (2015b, adapted from Figures 3–4), reproduced with permission ©ESO.

#### Proposed or unconfirmed planets

- *CM Dra*: from eclipse timings dating back to 1977, Deeg et al. (2008) proposed a third body of a few  $M_J$  and  $P = 18.5 \pm 4.5$  yr, or an object in the range  $1.5M_J - 0.1M_\odot$  with a period of hundreds to thousands of years. This has not been confirmed (Ofir, 2008).
- *QS Vir*: the  $P_{\text{orb}} = 3.6$ -h binary comprises a white dwarf primary and M4 secondary, in which the red dwarf is temporarily and marginally detached from its Roche lobe, no mass transfer is ongoing, and the cataclysmic variable is in a ‘hibernating’ state. Qian et al. (2010a) reported a  $6.4M_J$  planet in a  $P = 7.86$ -yr ( $a = 4.2$  au) orbit, with sinusoidal residuals of amplitude 12 s. The orbit is incompatible with subsequent ULTRACAM observations (Parsons et al., 2010a), although the latter identified a 250 s departure from linearity in eclipse times which they attributed to a third body in a highly elliptical orbit. Almeida & Jablonski (2011) proposed that the system contains two companions (9 and  $57M_J$ ), while Horner et al. (2013) showed that such planets would move on crossing orbits, dynamical unstable in  $\leq 1000$  yr, and concluding that they cannot exist.

- *LX Ser*: A  $7.5M_J$  tertiary was reported around this 0.158-d period deeply eclipsing cataclysmic variable by Li et al. (2017a).

- *NSVS 14256825*: The existence of two circumbinary planets (periods 3.5 and 6.9 yr, masses 2.9 and  $8.1M_J$ ), was inferred from eclipse timings of this post-common-envelope binary (Beuermann et al., 2012a; Almeida et al., 2013). Dynamical analysis of their long-term orbital stability (Wittenmyer et al., 2013a), as well as further analysis of the eclipse times (Hinse et al., 2014) appeared to refute their existence. With 83 new eclipse timings spanning a total of 17 years, Nasiroglu et al. (2017) excluded a 2-planet model, and proposed a single circumbinary object of brown dwarf mass ( $\geq 15M_J$ ) with  $e = 0.17$  and  $P \sim 10$  yr.

- *KIC-5095269*: From a search of more than 2000 eclipsing binaries observed by Kepler, Getley et al. (2017) identified a circumbinary planetary mass body, with  $M_p = 7.7M_J$ ,  $P_{\text{orb}} = 237.7$  d, around a  $1.2M_\odot$  primary and  $0.5M_\odot$  secondary in a 18.6-d orbit, dynamically stable over a  $10^7$ -yr numerical integration.

#### 4.5 Transit timing variations

The NASA Exoplanet Archive lists a number of ‘timing discoveries’ as resulting explicitly from the analysis of Kepler transit time variations (Section 6.20). In brief, candidate multiple transiting planets may be confirmed as planets as a result of their mutual transit timing variations, while additional (transiting or non-transiting) planets may be inferred from transit timing variations of a gravitationally-perturbed planet.

As of the end of 2017, the NASA Exoplanet Archive lists the following (Kepler) planets as having been *discovered* from transit timing variations (the corresponding primary identifier used in the archive is in parentheses): Kepler-19 c; Kepler-37 e; Kepler-46 c; Kepler-88 c (KOI-142 c); Kepler-122 f; Kepler-338 e; Kepler-414 b,c; Kepler-415 b,c; Kepler-416 b,c; Kepler-417 b,c; Kepler-419 c; and Kepler-1648 b (KIC-7917485 b, attributed to pulsation timing variations).



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# Microlensing

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BY THE END OF 2017, 53 exoplanets had been discovered through gravitational microlensing. The first unambiguous detection of a  $4M_J$  planet at  $a \sim 4$  au was reported in 2004, and the discovery of a  $5M_{\oplus}$  planet in 2006. A two-planet system was observed in 2008 in which orbital motion was measured during the lensing event, and measurement of the microlens parallax (and lens mass) in 2015. Evidence for free-floating planets was followed with a reasonably unambiguous candidate in early 2018. These confirm the technique as a powerful and independent exoplanet probe over an important region of mass and orbital radius. The start of ‘second-generation’ surveys, and plans for space measurements with Euclid and WFIRST, offer substantial prospects.

## 5.1 Introduction

**Gravitational lensing** In general relativity, the presence of matter (energy density) distorts spacetime, and the path of electromagnetic radiation is deflected as a result. Under certain conditions, light rays from a distant background object (the source) are bent by the gravitational potential of a foreground object (the lens) to create images of the source which are distorted (and possibly multiple), and which may be highly focused and hence significantly amplified. Its manifestation depends upon the fortuitous alignment of the background source, the intervening lens, and the observer.

Different regimes are generally recognised for gravitational lensing, depending on whether effects are discernible at an individual object level (*strong lensing*), or only in a statistical sense (*weak lensing*). Strong lensing can be further divided, somewhat subjectively according to telescope resolution, into *macrolensing* (resulting either in multiple resolved images, or in ‘arcs’ in which the source is both sheared and magnified) and *microlensing* (in which discrete multiple images are essentially unresolved). Lensing by planetary-mass objects is sometimes referred to as *nanolensing*, while the astrometric displacement predicted to accompany a high-proper motion foreground star is known as *mesolensing*.

Relative motion between source, lens and observer leads to time-varying amplification of the images, which may occur over time scales of hours, months or many years, depending on the nature of the source and lens. If the foreground lensing object is itself of complex gravitational morphology, whether a cluster of galaxies, or a star orbited by one or more planets, then the background source may show a more complex light curve resulting from the time-varying magnification during the evolving alignment geometry.

**Microlensing** In the microlensing regime, a term introduced by Paczyński (1986a), discrete images of the source are unresolved at typical telescope resolutions. The term embraces phenomena operating on galaxy scales (quasar microlensing) and on stellar mass scales and below (relevant for exoplanets). In the latter case, the primary lens is a single point mass of order  $1M_{\odot}$ , and the two images of a background source have a separation of order 1 mas, well below typical ground-based instrumental resolution.

In the typical domain of interest for exoplanet detection, the exoplanet system (host star and planet) acts as a multiple lens, and a more distant star within the Galaxy acts as a probing point source. The changing magnification of the sub-images due to the time-varying alignment geometry of the observer–lens–background source may lead to a significant intensity variation of the sum of the multiply lensed images over time scales of weeks. This changing intensity with time allows the event to be recognised as a microlensing event. Careful monitoring of the light curve as the alignment changes over several hours allows the additional lensing effects of an accompanying planet to be identified.

Microlensing provides a powerful route for the detection and characterisation of planetary systems. The basic experimental challenge is that significant magnification (brightening) requires extremely precise alignment of observer, source and lens, to within the angular Einstein radius, or around  $\sim 1$  mas.

Such an alignment probability for any given source star in the Galaxy is so low that very large numbers of

**Historical background:** The first observational confirmation of general relativistic light bending, based on the 1919 solar eclipse observed in Brazil, was reported by Dyson et al. (1920); later and more compelling astrometric confirmation included the 1973 solar eclipse observations (Brune et al., 1976; Jones, 1976), and the full-sky Hipparcos observations (Froeschlé et al., 1997b). The term ‘lensing’ in this context was used, pejoratively, by Lodge (1919), who argued that ‘*it is not permissible to say that the solar gravitational field acts like a lens, for it has no focal length.*’ The term has nevertheless persisted as a description of the phenomenon.

The possibility that gravitational lensing by a foreground object could result in two distinct images of a background star was pointed out by Eddington (1920). A qualitative description, and the possibility of a ring-shaped image, was suggested in a short communication by Russian physicist Orest Chwolson (1924) who noted ‘*Whether the case of a fictitious double star actually occurs, I cannot judge.*’ The problem was first considered quantitatively by Einstein (1936) and Link (1936). Einstein’s paper starts ‘*Some time ago, R.W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request.*’ Later he comments ‘*Of course, there is no hope of observing this phenomenon directly. First, we shall scarcely ever approach closely enough to such a central line. Second, [the angles] will defy the resolving power of our instruments.*’ Prescient papers by Zwicky (1937a,b) later argued that ‘*extragalactic nebulae offer a much better chance than stars for the observation of gravitational lens effects.*’

After a lapse of almost three decades, the subject was reopened with the independent work of Klimov (1963), Liebes (1964), and Refsdal (1964). Liebes (1964) first considered gravitational lensing as a method to detect planets around other stars, concluding that the primary effect would be to ‘*slightly perturb the lens action of these stars.*’ He also considered the detectability of unbound planet-sized bodies ‘*floating about the Galaxy,*’ but also concluded that the ‘*associated pulses would be so weak and infrequent and of such fleeting duration – perhaps a few hours – as to defy detection.*’

Walsh et al. (1979) discovered the first case of strong lensing, a double image of the distant quasar QSO 0957+561. The discovery marked the start of a substantial body of both theoretical and observational work, and more than a hundred multiple images of galaxy-lensed systems are now known. Arc-like images of extended galaxies were first reported by Lynds & Petrosian (1986) and Soucail et al. (1987). Mainly through subsequent HST observations, many examples are now known.

The first incomplete Einstein ring was reported by Hewitt et al. (1988), and a complete example, a little less than 1 arcsec in diameter around the radio source B1938+666, in which both lens and source are galaxies, was imaged in the near-infrared by HST–NICMOS (King et al., 1998). Again, dozens of examples of more-or-less complete Einstein rings are now known, both in the optical, in the near-infrared, and in the radio. Microlensing studies of Galactic structure, and the associated search for planets, was launched by the work of Paczyński (1986a,b, 1991) and Mao & Paczyński (1991).

potential sources have to be monitored, frequently and simultaneously, to have any chance of observing even a single favourable configuration. The Galactic bulge region, with its high stellar surface density, is therefore the target monitoring region of choice.

For configurations of relevance, a typical source lies at a distance of  $\sim 8$  kpc. In the unlensed state, it is generally faint or even invisible, and to first order is considered as a point source of light. Microlensing most effectively probes lens systems some half way to the source, where the host star (and any accompanying planets) may also be invisible. It is the time-varying behaviour of the magnified background star that probes the geometry and mass distribution of the foreground system.

In practice, a characteristically rising light curve of a given star, out of many (of order  $10^7 - 10^8$ ) being simultaneously monitored, indicates that a favourable alignment may be developing. For the first generation surveys, more intensive photometric monitoring was then initiated to properly sample the crucial diagnostic time period of a possible exoplanet alignment.

The light curve of the background star is the observational signature of microlensing, and encodes the geometry and mass distribution of the lens system.

**Further background** This treatment focuses on the specific applications to exoplanets. A wider treatment of gravitational lensing is given by Schneider et al. (2006b).

As the subject has developed, various reviews have been given on microlensing in general (e.g. Paczyński, 1996; Mollerach & Roulet, 2002; Wambsganss, 2006; Rahvar, 2015), and on planetary aspects in particular (e.g. Sackett, 1999, 2004; Wambsganss, 2004; Gould, 2005; Gaudi, 2008, 2012; Giannini & Lunine, 2013; Gould, 2016b).

## 5.2 Principles

### 5.2.1 Light bending

Formulae to analyse gravitational lensing were derived by Refsdal (1964), and are subsequently found in various forms throughout the literature. For the geometry shown in Figure 5.1, the deflection angle  $\alpha_{\text{GR}}$  for a light ray propagating past a lensing mass  $M_{\text{L}}$  with impact parameter  $b$  is (e.g. Will, 1993)

$$\alpha_{\text{GR}} = \frac{4GM_{\text{L}}}{c^2 b} = \frac{2R_{\text{S}}}{b}, \quad (5.1)$$

on condition that  $b \gg R_{\text{S}}$ , where  $R_{\text{S}}$  is the corresponding Schwarzschild radius

$$R_{\text{S}} = 2GM_{\text{L}}/c^2, \quad (5.2)$$

where  $G$  is the gravitational constant and  $c$  is the speed of light. A rigorous solution of the general relativistic equations of motion for the coupled spacetime and matter is not required, because the bending of spacetime by exoplanet systems is always small.

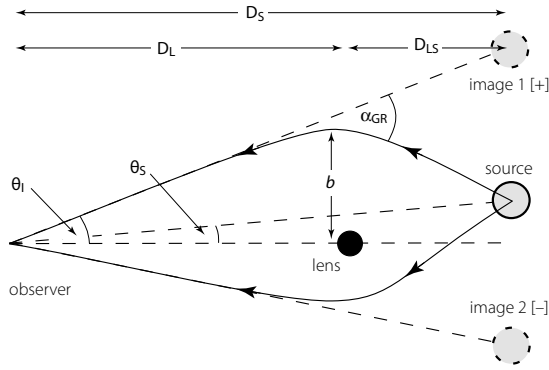


Figure 5.1: Lensing schematic for a point mass lens  $M_L$  at distance  $D_L$ , offset by the small angle  $\theta_S$  from the direct line from observer to source. A light ray from the source, passing the lens at distance  $b$ , is deflected by an angle  $\alpha_{GR}$ . An observer sees one image of the source displaced to angular position  $\theta_I = b/D_L$  on the same side as the source, and a second image on the other.

The condition on  $\alpha_{GR}$  that a deflected light ray from the source reaches the observer follows purely from the trigonometry of Figure 5.1. In the usual approximation of small angles, with  $D_L$  and  $D_S$  signifying the distances to the lens and source, and  $D_{LS} = D_S - D_L$  (applicable for a Euclidean metric, i.e. for local events, but not for lensing over cosmological distances), the angle between source and lens is

$$\theta_S D_S = \frac{D_S}{D_L} b - \alpha_{GR} D_{LS} = \frac{D_S}{D_L} b - \frac{2R_S}{b} D_{LS}. \quad (5.3)$$

With  $\theta_I = b/D_L$  denoting the angle between the deflecting mass and the deflected ray, this can be written

$$\theta_S = \theta_I - 2R_S \frac{D_{LS}}{D_L D_S} \frac{1}{\theta_I}. \quad (5.4)$$

This is a form of the *lens equation*, which describes the mapping, in the lens plane, from an image position  $\theta_I$  to the source position  $\theta_S$ . Being quadratic in  $\theta_I$ , it has two (image) solutions.

**Einstein radius** It is convenient to define a characteristic angle  $\theta_E$ , the *angular Einstein radius*, and a characteristic length scale in the lens plane  $R_E$ , the (linear) *Einstein radius*, given by

$$\theta_E = \left[ 2R_S \frac{D_{LS}}{D_L D_S} \right]^{1/2} = \left[ \frac{4GM_L}{c^2} \frac{D_{LS}}{D_L D_S} \right]^{1/2} \quad (5.5)$$

$$R_E = \theta_E D_L = \left[ 2R_S \frac{D_L D_{LS}}{D_S} \right]^{1/2}. \quad (5.6)$$

Then the lens equation (Equation 5.4) can be written

$$\theta_I^2 - \theta_S \theta_I - \theta_E^2 = 0. \quad (5.7)$$

This has two solutions

$$\theta_{+,-} = \frac{1}{2} \left( \theta_S \pm \sqrt{\theta_S^2 + 4\theta_E^2} \right), \quad (5.8)$$

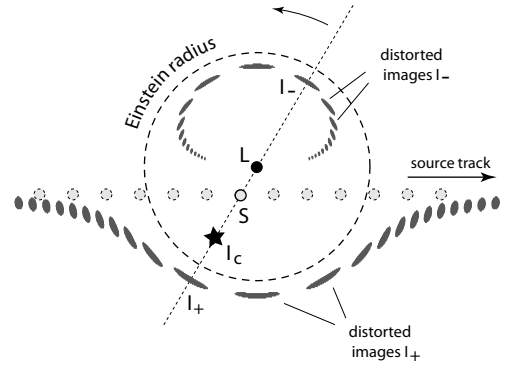


Figure 5.2: Schematic of (astrometric and photometric) microlensing. A background source (small grey circles,  $S$ ) moves behind a foreground lens ( $L$ ). Here  $L$ , and its Einstein radius, are stationary.  $S$  and  $L$  along with the two distorted images ( $I_{\pm}$ , inside and outside the Einstein radius), and their centroid ( $I_c$ ) remain colinear. As the source moves past the lens, this connecting line rotates by almost  $180^\circ$  (here counter-clockwise), and the image centroid follows a correspondingly non-linear path. Adapted from Paczyński (1996, Figure 3).

showing that the source has two images, one on each side of the lens (a negative value of  $\theta$  meaning that the image is on the other side of the lens from the source). The angular separation between the two images is

$$\Delta\theta \equiv \theta_+ - \theta_- = \sqrt{\theta_S^2 + 4\theta_E^2}. \quad (5.9)$$

In the hypothetical case of perfect observer–lens–source alignment ( $\theta_S = 0$ ), the configuration is rotationally symmetric about the line-of-sight to the lens, and the two images merge to form a ring (an *Einstein ring*) of angular radius  $\theta_E$  (the Einstein radius). For all other source positions, one image lies inside  $\theta_E$  and one lies outside (Figure 5.2).

Introducing relevant numerical quantities provides an estimate of the Einstein radius typical for exoplanet investigations. Equations 5.5 and 5.6 can be written

$$\theta_E \approx 1.0 \left( \frac{M_L}{M_\odot} \right)^{1/2} \left( \frac{D_L}{8 \text{ kpc}} \right)^{-1/2} \left( \frac{D_{LS}}{D_S} \right)^{1/2} \text{ mas}, \quad (5.10)$$

$$R_E \approx 8.1 \left( \frac{M_L}{M_\odot} \right)^{1/2} \left( \frac{D_S}{8 \text{ kpc}} \right)^{1/2} \left( \frac{D_L D_{LS}}{D_S^2} \right)^{1/2} \text{ au}. \quad (5.11)$$

The former shows that for a source roughly at the distance of the Galactic centre (assumed to lie at 8 kpc), and a lens with  $M_L = M_\odot$  half way to the source, typical image separations are of order the Einstein angular radius  $\theta_E \sim 1$  mas. This is well below the angular resolution of most ground-based instruments; consequently the image separation, and its variation with time, are generally undetectable. The latter shows that the Einstein radius for a typical host star is  $R_E \approx 4$  au. Being of order of the orbital radius of planets in the solar system, this is a particularly fortuitous scale length for probing exoplanets.

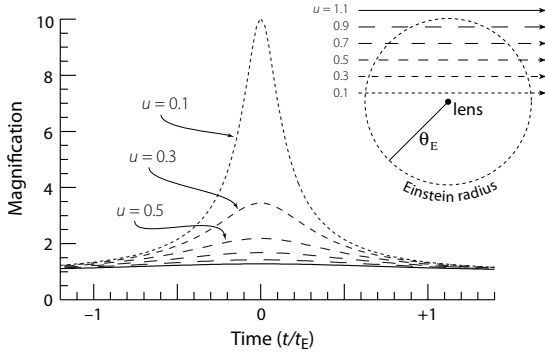


Figure 5.3: Theoretical microlensing light curves for a point source and single lens, with a constant relative transverse velocity between them. For the geometry depicted in the inset, the Einstein radius is shown dashed, and a series of trajectories are shown with their corresponding values of  $u = \theta_S/\theta_E$ . Microlensing events passing close to the projected lens position are then highly amplified (Equation 5.15), with the magnification becoming rapidly more pronounced with decreasing  $u$ . Adapted from Paczyński (1996, Figures 4–5).

### 5.2.2 Magnification

Light deflection in the gravity field changes both the direction of a light ray and the cross section of a bundle of rays. Brightening of the two images occurs because the flux from each is the product of the (constant) surface brightness of the source and the (enlarged) solid angle subtended by the distorted image. Since general relativistic light bending is wavelength independent, the microlensing light curve is consequently *achromatic*.

The *magnification* for each image is given by the ratio of the image area to the source area

$$A_{\pm} = \left| \frac{u_{\pm}}{u} \frac{du_{\pm}}{du} \right|. \quad (5.12)$$

For a Schwarzschild (point mass) lens, and with the projected lens–source separation expressed in units of the Einstein radius

$$u \equiv \frac{\theta_S}{\theta_E}, \quad (5.13)$$

the two images have individual magnifications

$$A_{\pm} = \frac{1}{2} \left( \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \pm 1 \right), \quad (5.14)$$

although only the total magnification is observable

$$A \equiv A_+ + A_- = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \quad (5.15)$$

$$\approx u^{-1} \quad \text{for } u \ll 1 \quad (5.16)$$

$$\approx 1 \quad \text{for } u \gg 1. \quad (5.17)$$

For perfect observer–lens–source alignment  $u \rightarrow 0$ ,  $A \rightarrow \infty$ , and the magnification is then formally infinite. For

**Early microlensing surveys:** The first microlensing surveys were motivated by the search for evidence of dark matter in galaxy halos probed by quasars (Gott, 1981; Paczyński, 1986b). Even for such ‘normal’ microlensing – that is, before accounting for the still smaller probabilities of detecting planetary perturbations – the alignment required for a detectable brightening is so precise that the chance of substantial microlensing magnification is extremely small. It is of order  $\sim 10^{-6}$  for background stars even in the denser directions of the Galactic bulge, nearby Magellanic Clouds, or nearby spiral galaxy M31, even if all the unseen Galactic dark matter were composed of compact macroscopic objects capable of lensing.

Only since 1993, when massive observational programmes capable of surveying millions of stars got underway, was photometric microlensing observed by the EROS (Expérience de Recherche d’Objets Sombres, Aubourg et al. 1993), OGLE (Optical Gravitational Microlensing, Udalski et al. 1993), MACHO (Massive Compact Halo Objects, Alcock et al. 1993), DUO (Disk Unseen Objects, Alard 1996), and MOA (Microlensing Observations in Astrophysics, Muraki et al. 1999) projects. Early reviews of these results were given by Paczyński (1996) and Gould (1996).

Using their achromatic nature to distinguish them from intrinsic source variability, several thousand microlensing events have been detected in the Galaxy (with some 10% showing binary lens structure), and many individual events and statistical results have been published.

These impressively vast monitoring programmes have demonstrated that the excess microlensing seen towards the Large Magellanic Cloud by the MACHO group (Alcock et al., 2000) requires at most 20% of the Galaxy’s dark matter in the form of stellar mass objects, while the results of the EROS group (Tisserand et al., 2007) suggest that much of the excess may be caused by stars within the LMC itself.

With the constraints on dark matter largely resolved, the emphasis of observations subsequently focused on exoplanets, with the first detection in 2003.

the realistic case of a finite source size, and partly because this diverging condition arises from the simplified treatment of geometrical optics, the magnification is in practice always finite.

The total magnification varies as a function of time due to the relative transverse motion between source, lens, and observer (Figure 5.3). For a given relative transverse velocity between source and lens,  $v_{\perp}$ , a typical time scale for a lensing event is given by the *Einstein radius crossing time*

$$t_E = R_E/v_{\perp} \approx 70 \left( \frac{M_L}{M_{\odot}} \right)^{\frac{1}{2}} \left( \frac{D_S}{8 \text{ kpc}} \right)^{\frac{1}{2}} \left( \frac{D_L D_{LS}}{D_S} \right)^{\frac{1}{2}} \left( \frac{v_{\perp}}{200 \text{ km s}^{-1}} \right)^{-1} \text{ days}. \quad (5.18)$$

Again, for a source in the bulge (at 8 kpc), and a lens of  $1M_{\odot}$  half way to the source, the Einstein time scale for the resulting microlensing event is  $\approx 35$  d.

Equivalently, in angular measure, the Einstein time scale is related to the (unknown from the event itself)

**Development of microlensing planet studies:** A large body of theoretical and simulation studies has been carried out as part of the development of the framework for microlensing studies, both before and after the first planet detections. Chronologically Mao & Paczyński (1991) and Gould & Loeb (1992) investigated lensing when one or more planets orbit the primary lens, finding that detectable fine structure in the photometric signature of the background object occurs relatively frequently, even for low-mass planets. Gould & Loeb (1992) found that the probability of detecting such fine-structure is about 17% for a Jupiter-like planet (i.e. at about 5 au from the central star), and 3% for a Saturn-like system; these relatively high probabilities occur specifically when the planet lies in the ‘lensing zone’, between about 0.6–1.6  $R_E$ .

Subsequent work included determination of detection probabilities (Bolatto & Falco, 1994), extension to Earth-mass planets including the effects of finite source size (Bennett & Rhie, 1996; Wambsganss, 1997), determination of physical parameters (Gaudi & Gould, 1997), detection rates for realistic observational programmes (Peale, 1997; Gaudi & Sackett, 2000), distinguishing between binary source and planetary perturbations (Gaudi, 1998; Jung et al., 2017), detection rates for high-magnification events (Griest & Safizadeh, 1998), multiple planets in high-magnification events (Gaudi et al., 1998), repeating events due to a multiple planetary system (Di Stefano & Scalzo, 1999b), caustic-crossing configurations (Graff & Gaudi, 2000; Bozza, 2000), multiple planet anomalies (Han et al., 2001a), probability rates (Peale, 2001), simulations of high magnification events (Rattenbury et al., 2002), effects of wide orbit planets (Han & Kang, 2003; Han et al., 2005), effects of multiple planets (Han, 2005a), properties of central caustics (Chung et al., 2005; Han, 2006a), sensitivity to Earth-mass planets (Park et al., 2006), and double-peaked high magnification events (Han & Gaudi, 2008).

lens–source relative proper motion,  $\mu_{LS}$ , by

$$t_E = \frac{\theta_E}{\mu_{LS}}. \quad (5.19)$$

### 5.2.3 Optical depth and event rate

A *significantly lensed source* can be loosely defined as one with angular separation from a foreground lens  $\beta \leq \theta_E$ . The combined magnification of the two images of a source within that circle is larger than  $A \geq 3/5^{0.5}$ , i.e.  $\Delta m \geq 0.32$  mag (Equation 5.15 with  $u \leq 1$ ), a brightness increase straightforward to detect with reasonable photometric accuracy. Correspondingly, the *cross section for gravitational microlensing* is generally taken to be equal to the area of the Einstein circle.

**Optical depth** The probability that any given star is being significantly lensed at any given time by a foreground compact object is referred to as the *lensing optical depth*,  $\tau$  (Paczynski, 1996; Mao, 2008; Gaudi, 2012). The optical depth is therefore the fraction of solid angle covered by the Einstein rings of all foreground lenses.

The number of lenses in the volume of space subtending solid angle  $\Omega$  at distance  $D_L$  in a shell of thickness  $dD_L$  is  $n(D_L) \Omega D_L^2 dD_L$ , where  $n$  is the number density of lenses. Assuming all lenses have an angular Einstein ring radius  $\theta_E$ , the contribution of the shell to the optical depth is therefore  $n(D_L) \pi \theta_E^2$ . Integrating along the line-of-sight

$$\tau = \frac{1}{\Omega} \int_0^{D_S} n(D_L) \Omega D_L^2 \pi \theta_E^2 dD_L = \int_0^{D_S} n(D_L) D_L^2 \pi \theta_E^2 dD_L. \quad (5.20)$$

The mass density of lenses of mass  $M_L$  is related to the number density by  $n = \rho/M_L$ . Since  $\pi \theta_E^2 \propto M_L$ , the lens mass drops out of the expression for the optical depth. Although this derivation assumes a single lens mass, the same is also true for a more general mass distribution.

Thus, the optical depth depends only on the mass density along the line-of-sight, and not on the mass function of lenses. Inserting the expression for the angular Einstein ring radius, and scaling the distance along the line-of-sight to the distance to the source, gives

$$\tau = \frac{4\pi G D_S^2}{c^2} \int_0^1 \rho(x) x(1-x) dx. \quad (5.21)$$

A more complete expression integrates over the source distances, weighting by the density of sources (Kiraga & Paczyński, 1994; Han & Gould, 1995; Wood & Mao, 2005). For a simplified model of the Galaxy as a spherical, self-gravitating system of lenses centred at the Galactic centre, with uniform density  $\rho_0$ , total mass  $M_0$  interior to the solar circle, circular velocity at the solar circle  $V^2 = GM_0/D_S$ , and density  $\rho_0 = 3M_0/(4\pi D_S^3)$ , then integrating Equation 5.21 gives (for  $V = 220$  km s $^{-1}$ )

$$\tau = \frac{2\pi}{3} \frac{G\rho_0}{c^2} D_S^2 = \frac{GM_0}{2c^2 D_S} \approx \frac{V^2}{2c^2} \approx 2.7 \times 10^{-7}. \quad (5.22)$$

Observational estimates of the optical depth toward the Galactic centre are some 3–10 times larger (Afonso et al., 2003; Popowski et al., 2005; Sumi et al., 2006), due to the flattened disk and the bar.

**Event rates** The *microlensing event rate*,  $\Gamma$ , is the rate at which a given background star undergoes a significant microlensing event due to a foreground lens. The probability that a given source will exhibit a significant event in time  $dt$  is the fraction of sky covered by the solid angle of angular width  $2\theta_E$  and transversal length  $\mu_{LS} dt$ , integrated over all lenses along the line-of-sight. If all events have time scale  $t_E$  then, in analogy to the optical depth, the event rate is

$$\begin{aligned} \Gamma &= \frac{1}{\Omega} \int_0^{D_S} n(D_L) \mu_{LS} dt \Omega D_L^2 2\theta_E dD_L \\ &= \frac{2}{\pi} \frac{dt}{t_E} \left[ \int_0^{D_S} n(D_L) D_L^2 \pi \theta_E^2 dD_L \right] = \frac{2}{\pi} \frac{\tau}{t_E}, \end{aligned} \quad (5.23)$$

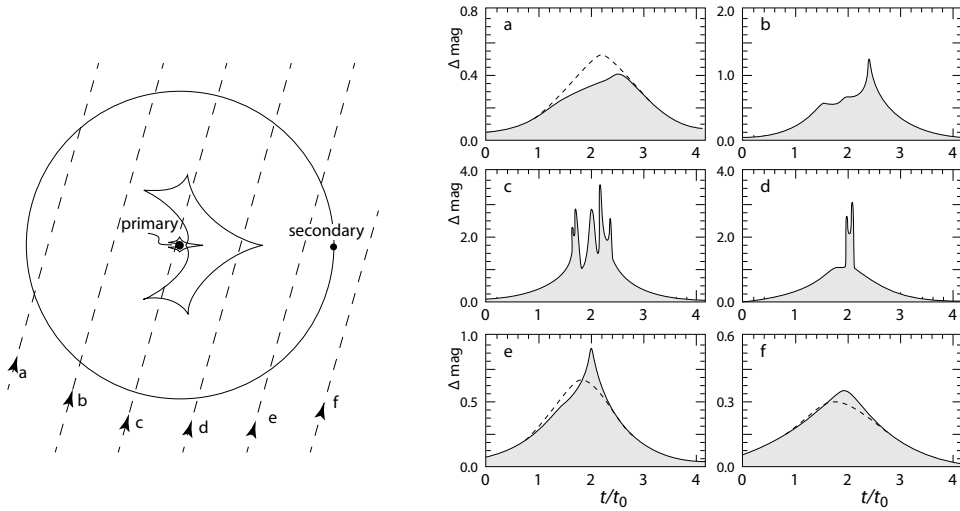


Figure 5.4: Left: binary lens microlensing geometry. The primary of  $1M_{\odot}$  is at the centre, and the secondary of mass  $0.1M_{\odot}$  (larger central caustic) or  $0.01M_{\odot}$  (smaller central caustic) at the right, on the Einstein ring of the primary. Three microlens images exist for a source located outside the respective caustic, while a source inside them forms five. The parallel dashed lines show six source trajectories for which the light variations are shown for a  $0.01M_{\odot}$  secondary (right panels). Bright spikes occur when a source crosses a caustic, or approaches a cusp (c and d). For the low-amplitude light curves (a, e, f), dashed lines show the light curves for single-lens events matching the wings. From Mao & Paczyński (1991, Figures 1–2), by permission of IOP Publishing/AAS.

where  $\mu_{LS} = \theta_E/t_E$  (Equation 5.19), and where the final expression is in terms of the optical depth (Equation 5.20). The observed median time scale for events towards the Galactic bulge of  $\sim 20\text{--}30$  d gives an event rate  $\Gamma \sim [\tau/10^{-6}] \cdot 10^{-5} \text{ yr}^{-1}$ .

A more rigorous determination of the event rate (e.g. Griest, 1991; Kiraga & Paczyński, 1994; Poleski, 2016) must account for the distribution of source densities and distances (typically a few kpc centred near the Galactic centre), the distribution of lens densities and distances (from a few hundred pc to the source distance), and the velocity distributions of the lenses and sources (together determining  $\mu_{LS}$ ), and in particular the broad velocity distribution of Galactic bulge stars. It must also integrate over an assumed mass function of the lenses (covering four orders of magnitude to include free-floating planets, brown dwarfs, stars, and stellar remnants).

The resulting microlensing event rate per star is very low, implying that a large number of sources must be monitored to have any prospect of detecting a significantly lensed event. For example, OGLE currently monitors  $2.5 \times 10^8$  sources in some 80 sq. deg., from which they generate alerts for around 1500 events during the 8-month season when the Galactic bulge is visible.

**Simulations** The Manchester–Besançon Microlensing Simulator (MaB $\mu$ LS), based on the Besançon population synthesis model of the Galaxy (box, page 380), provides microlensing maps of the Galaxy’s inner regions, generating optical depth, event rate or event duration maps as a function of bandpass, sky area, range of source apparent magnitude, and lens population (Kerins et al., 2009; Awiphan et al., 2016b).

## 5.3 Light curves

### 5.3.1 Single lens characterisation

Writing the projected lens–source separation resulting from uniform rectilinear motion as

$$u = \left( \left[ \frac{t - t_0}{t_E} \right]^2 + u_0^2 \right)^{1/2}, \quad (5.24)$$

shows that the light curve for a single lensing event depends on three parameters (in addition to the unlensed flux of the background star, which may or may not be detectable in the absence of microlensing): the Einstein radius crossing time  $t_E$ ; the time of peak magnification  $t_0$  (at which  $u$  is a minimum, and  $A$  is a maximum), and the minimum separation  $u_0$ , which determines the peak magnification and also the specific form of the light curve (Figure 5.3).

Normal (single lens) microlensing events yield only one physically relevant parameter, the Einstein time scale, derived from the event duration. As evident from Equation 5.18 this is a degenerate combination of  $M_L$ ,  $D_L$  (or, more strictly for a source at finite distance, the lens–source relative parallax), and the lens–source relative transverse velocity  $v_{\perp}$ . If the lens is unseen, its mass and distance can be determined only in particularly favourable circumstances (§5.5).

### 5.3.2 Binary lens characterisation

Compared to the smooth light curves of single-lens microlensing, the existence of a planet can result in



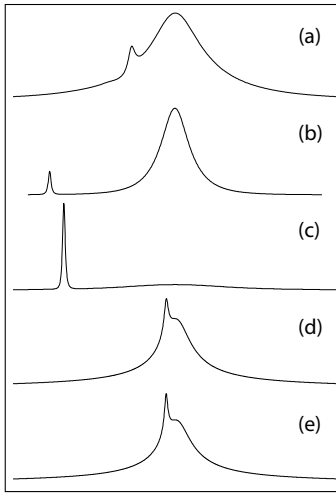


Figure 5.5: Illustrative classification of perturbation types. (a) projected star–planet separation similar to  $R_E$  (of the primary); (b) projected separation substantially larger than  $R_E$ , and the source trajectory passes the effective magnification regions of both primary and planet; (c) as (b), but the trajectory only passes the effective magnification region of the planet; (d) wide-separation planet, when the trajectory passes close to the primary; (e) the star–planet separation is much smaller than  $R_E$ , and the trajectory passes close to the primary. From Han (2007b, Figure 1), by permission of IOP Publishing/AAS.

additional short-duration peaks depending on how the source path crosses the lens projection (Figure 5.4).

In a binary lens system<sup>1</sup> with projected component separation  $a$ , the second lens introduces three further parameters (in addition to  $t_E$ ,  $t_0$  and  $u_0$ ): the mass ratio of the two components  $q = M_p/M_*$ , the projected star–planet separation at the time of the lensing event in units of the Einstein radius for the total mass  $d = a/R_E$ , and the angle of the source trajectory relative to the binary axis  $\alpha$ . Although determined by only a few parameters, their combinations lead to a very wide diversity of binary lens light curves, discussed further in §5.3.5. A qualitative classification of perturbation types, given by Han (2007b), is shown in Figure 5.5.

General properties of the two-point lens system were explored by Schneider & Weiss (1986), and the first examples of binary microlensing light curves were presented by Mao & Paczyński (1991, cf. Figure 5.4).

Planetary event durations scale with  $q^{0.5}$  (Equation 5.18), and generally last less than a day, compared with a typical primary lens event of 30–40 d. As  $q$  decreases, the peak signals become rarer and briefer: for Earth-mass planets, typical time scales are  $\sim 3$ –5 h.

<sup>1</sup>In the literature, the term ‘binary lens’ generally refers to a two-point star–planet lens system. Depending on context, it may also refer to a binary *star* lens, with or without a planet.

### 5.3.3 Multiple point mass lenses

The lens equation for a single point-mass lens (Equation 5.4) can be generalised, most conveniently vectorially, to a system of  $N_l$  lenses (so accommodating the effects of multiple planets, circumbinary planets, or planets with moons) as

$$\mathbf{u} = \mathbf{y} - \sum_i^{N_l} \epsilon_i \frac{\mathbf{y} - \mathbf{y}_i}{|\mathbf{y} - \mathbf{y}_i|^2}, \quad (5.25)$$

where  $\epsilon_i \equiv m_i/M_{\text{tot}}$  are the individual lens masses,  $\mathbf{u} \equiv \beta/\theta_E$  is the source position,  $\mathbf{y} \equiv \theta/\theta_E$  the image positions,  $\mathbf{y}_i \equiv \theta_i/\theta_E$  are the positions of lens  $i$ , and normalisation is (arbitrarily but conveniently) with respect to the Einstein radius of the total lens mass  $M_{\text{tot}} \equiv \sum_i^{N_l} m_i$ .

Recast in complex coordinates (Witt, 1990), the lens equation can be written

$$\xi = z - \sum_i^{N_l} \frac{\epsilon_i}{\bar{z} - \bar{z}_i}, \quad (5.26)$$

where  $\xi = (u_1, u_2)$  are the source positions,  $z = (y_1, y_2)$  are the images, and  $\bar{z}$  denotes complex conjugate. This polynomial of order  $N_l + 1$  can be solved numerically, yielding  $N_l + 1$  roots, of which no more (and generally less) than  $5(N_l - 1)$  (for  $N_l \geq 2$ ) are true solutions of the lens equation (e.g. Gaudi, 2012, and references).

More generally (cf. Equation 5.14) the magnification of individual images is given by the inverse of the Jacobian determinant of the coordinate transformation from image to source plane at the image position, where

$$\det J = \sum_i^{N_l} \frac{\epsilon_i}{(\bar{z} - \bar{z}_i)^2}. \quad (5.27)$$

Accordingly, any companion to a single lens mass will distort the primary lens’s magnification field, inducing an ‘astigmatism’ or ‘caustic structure’ near the peak.<sup>2</sup>

Noting that the image magnifications can be positive or negative, and that the images are generally unresolved, the total magnification,  $A = \sum_j |A_j|$ , can result in the rich and ‘spiky’ structure often seen in planetary lensing light curves (e.g. Figures 5.4, 5.11 and 5.20–5.28).

The properties and various degeneracies of a lens system comprising a primary star plus two planets are analysed by Song et al. (2014).

<sup>2</sup>In optics, a caustic is the envelope of light rays reflected or refracted by a curved surface or object, resulting in concentrations of light, and informally the term may refer to the patches of light or their bright edges. Familiar examples include light shining through a wine glass onto a tablecloth, or rippling caustics formed when light shines through waves on the surface of a swimming pool. The term originates from the Greek for burning, recalling that such concentrations of sunlight can burn.

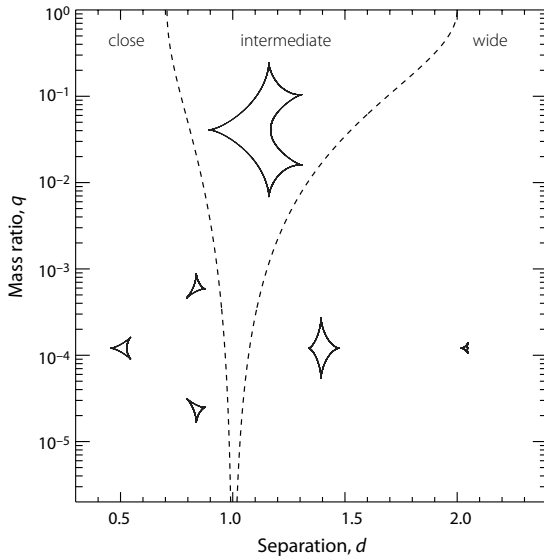


Figure 5.6: The three topologies of binary lenses as derived by Cassan (2008): the close binary lens (left), which involves a central caustic plus two off-axis small secondary caustics (plotted for  $d = 0.8$  and  $q = 10^{-2}$ ), the intermediate binary (middle, assuming  $d = 1$  and  $q = 10^{-2}$ ) with a single caustic, and the wide binary (right,  $d = 1.6$  and  $q = 10^{-2}$ ) with a central caustic and an isolated secondary caustic. When  $q \rightarrow 0$ , the extension of the intermediate domain also tends to zero. From Cassan (2008, Figure 1), reproduced with permission © ESO.

### 5.3.4 Critical curves, caustics, and cusps

Regions in the lens plane where the determinant of the Jacobian vanishes, and the magnification according to Equation 5.27 is formally infinite, are termed *critical curves*. Corresponding points in the source plane, found from the mapping given by the appropriate lens equation, are termed *caustics*. For a system of point masses, caustic curves comprise multiple concave segments (folds or branches) that meet at *cusps* (and where, formally, the tangents of each branch are equal).

For a single point lens, the caustic for any source distance is the single point behind the lens, and the critical curve (the image positions of these caustics) is the Einstein ring. High-magnification events (§5.3.7) occur when the source approaches a caustic, with peak magnification at the projected distance of closest approach.

### 5.3.5 Binary lens caustics

Binary lens caustics play a central role in the interpretation of exoplanet microlensing light curves, and there is an extensive literature on the behaviour near folds and cusps, as well as on robust and efficient algorithms to compute source positions and magnification maps (e.g. Gaudi, 2010, Section 2.2.4 and references; see also §5.4).

Usually, two of the roots of the (complex) fifth-order lens equation (Equation 5.26) are spurious, and just

three unresolved microimages combine to produce the apparent brightness of the source. The caustics delineate the boundaries of the regions in the source plane where there are three or five images.

A binary lens has one, two, or three closed non-intersecting caustic curves, such that whenever the source crosses a caustic, precisely two images appear or vanish together, producing dramatic spikes in the light curve (Figure 5.4, curves c, d). Spikes may also be produced when a source moves close to a cusp (curve b). When the source trajectory is far from the caustics, the light curves are less dramatic, although the binary lens imposes asymmetry (curves a, e, f).

For a lens consisting of two point-like objects (specifically, here, a star and an orbiting planet), which of the three caustic topologies is realised (and their positions and shapes) is determined by two parameters: the planet-to-star mass ratio  $q = M_p/M_*$ , and the instantaneous angular star-planet separation  $d$  (in units of  $\theta_E$  for the total mass). Expressions for the critical values of  $d$  for which the topology changes for arbitrary  $q$  are given by Erdl & Schneider (1993).

**Topological boundaries** For small mass ratios,  $q \ll 1$ , the topological boundaries for a given  $q$  are (Dominik, 1999; Cassan, 2008; Gaudi, 2012)

$$d_c \simeq 1 - 3q^{1/3}/4 \quad (5.28)$$

$$d_w \simeq 1 + 3q^{1/3}/2. \quad (5.29)$$

These critical values define the regimes of close ( $d < d_c$ ), intermediate ( $d_c < d < d_w$ ), or wide ( $d > d_w$ ) topologies (illustrated in Figure 5.6):

(i) close topologies result in three caustics: a *central* caustic, and two larger ‘triangular’ *planetary caustics* on opposite sides of the star-planet axis;

(ii) wide topologies results in two caustics: a central caustic, and a larger four-cusped caustic on the star-planet axis, also referred to as the *planetary caustic*;

(iii) intermediate topologies result in a single caustic.

For a given mass ratio  $q$ , the intermediate caustic is larger than the central or planetary caustics, resulting in a relatively large cross section and, although (generally) relatively weak, perturbations over a significant fraction of the primary event time scale. The intermediate caustic, representing the merging of the planetary and central caustics for a star-planet projected separation  $d \sim 1$ , is also referred to as a *resonant caustic* (Chung, 2009; Gaudi, 2012). Their extended duration, and the fact that their shape depends sensitively on  $d$ , implies that such events are also potential probes of the planet’s orbital motion (§5.5.4).

Detailed discussion of these various topologies is given by Gaudi (2012), and other configurations continue to be described (e.g. Liebig et al., 2015; Luhn et al., 2016; Ryu et al., 2016b,c; Han et al., 2017a).

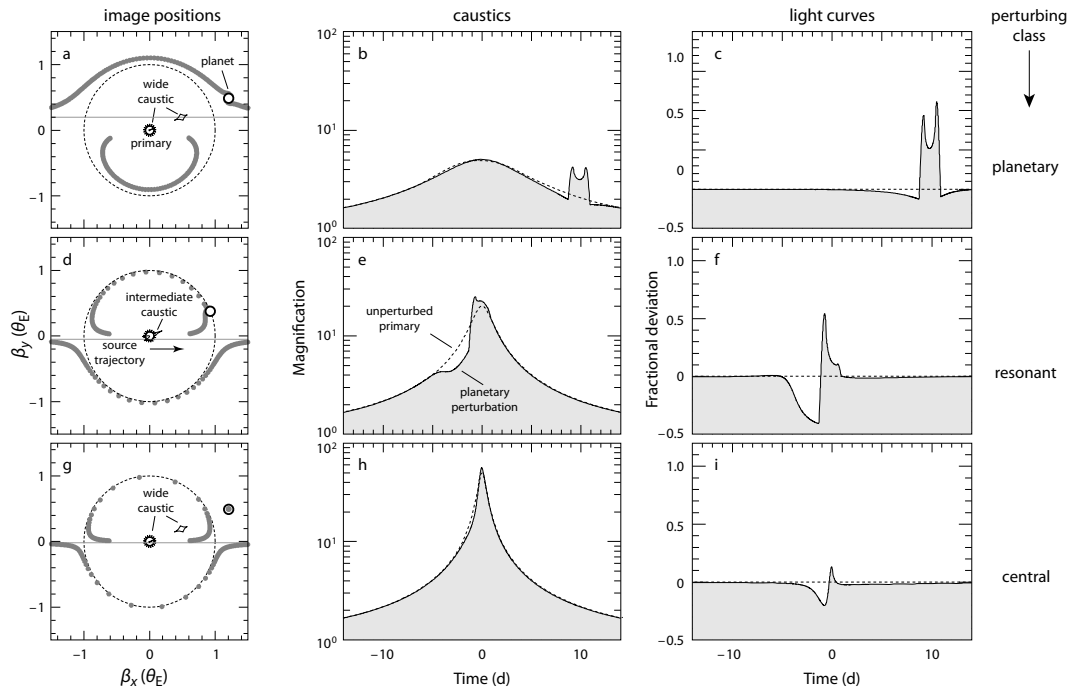


Figure 5.7: The three classes of planetary perturbations to primary microlensing events: planetary, resonant, and central. The image positions diagrams (a, d, g) show the source trajectory (horizontal line), the primary (at the origin) with its Einstein ring (dashed circle), planet (mass ratio  $q = 0.003$ , open circle), and successive image positions (grey circles). Light curves (c, f, i) show the unperturbed primary (dashed) and planetary perturbation (solid), assuming  $t_E = 20$  d, and a finite source size  $\rho = 0.01$  (corresponding to a typical Galactic bulge clump giant). From Gaudi (2012, Figure 5), by permission, Annual Reviews ©2012.

**Detection domains** In consequence, and as shown in Figure 5.7, there are four qualitatively different ways that planets can be detected through their microlensing light curves (Gaudi, 2012; Clanton & Gaudi, 2014a):

- (a) source crossing of a planetary caustic from either close- or wide-separation planets in low magnification events. Although such perturbations are unpredictable, this is a favourable configuration for planet detection because the planetary caustics have the largest area on the sky, and thus the highest probability of perturbing a source image magnified by the primary (host star) lens;
- (b) perturbations from the central caustic resulting from either close or wide planets in high-magnification events. Although relatively rare, such events can be recognised in advance of the peak magnification;
- (c) resonant caustic perturbations in modest- to high-magnification events;
- (d) isolated, short time scale events resulting from wide-separation planets, or from free-floating planets.

While only a minority of the first-generation planet detections have been detected via the (unpredictable) planetary caustic, more should be detected with the high-cadence monitoring of the second-generation surveys (Chung & Lee, 2011b).

**Higher order effects** Due to the pronounced variations of magnification with respect to source–lens alignment, light curves with a caustic crossing, or those resulting from a close approach to a cusp, can reveal features attributable to the finite size of the source star, limb darkening of the source, orbital motion, and other more subtle effects (§5.5-5.6).

### 5.3.6 Magnification maps

In the example magnification maps given in Figure 5.8, and following Griest & Safizadeh (1998), the primary (star) lens is located at the origin, and the planet is along the positive  $x$ -axis at  $d$ . The point-like single lens *central caustic* becomes a tiny wedge-like feature, still located near  $x = 0$ , while one or two new caustics appear depending on the planet position. For  $d > 1$  there is a new diamond-shaped *planetary caustic* located on the same side of the lens as the planet with a predominantly excess magnification, while for  $d < 1$  two small triangular-shaped caustics appear close together on the opposite side of the lens, now with a pronounced magnification deficit between them (Cassan, 2008; Wambsganss, 1997). The light curve of a moving source tracks a slice across the magnification contours in this  $xy$  plane.

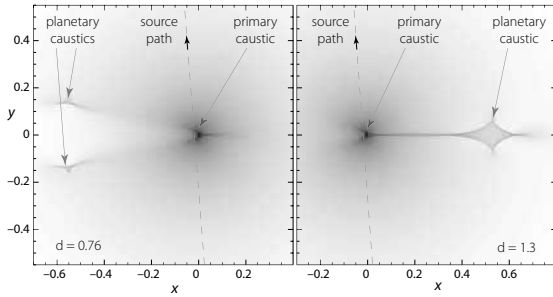


Figure 5.8: Caustics for a planet-to-lens mass ratio  $q = 0.006$  ( $\sim 6M_J/1M_\odot$ ), generated by inverse ray shooting for models of OGLE-2005-BLG-71. The primary lens lies at the origin, with the planet along the  $x$ -axis with separation  $d$  (in units of  $\theta_E$ ). Left:  $d = 0.76$ ; right: for the dual position at  $d = 1/0.76 = 1.3$ . Intensity is proportional to logarithmic magnification. Dashed lines show the model source star track, passing close to the central stellar caustic. Figures provided by Daniel Kubas.

The position of the planetary caustics can be reasoned as follows (Griest & Safizadeh, 1998, Appendix A). Since a planet mass is much smaller than the primary lens mass, its area of influence is small when measured in units of  $R_E$ . Thus, to a first approximation, the planet can have a large effect only when its position is near one of the main images. The relation between planet and caustic positions should then correspond to the relation between image and source positions (Equation 5.8). Inverting this equation (again, expressed in units of  $R_E$ ) gives the expected position of the planetary caustic, which therefore lies along the  $x$ -axis at

$$x_c \approx (d^2 - 1)/d. \quad (5.30)$$

The mass ratio  $q$ , but not  $M_p$  itself, can generally be determined from the duration of the planetary perturbation. Determination of the star–planet separation (in units of  $R_E$ , which itself is typically unknown), can be made from the light curve, and a first-order estimate of  $d$  can be found as follows. If a planetary deviation is observed at a time when the best-fit single lens light curve results in a certain magnification  $A$ , the corresponding lens–source separation  $u_c$  can be estimated from Equation 5.15. Then the planet position is given by the solution to Equation 5.30,

$$d = \frac{1}{2} \left( u_c \pm \sqrt{u_c^2 + 4} \right). \quad (5.31)$$

From Figure 5.8 it can be seen that the two solutions for a given  $u_c$  have similar magnification patterns in the vicinity of the central caustic, although precise photometry may allow distinguishing between the two.

**Algorithms** Algorithms to determine magnification maps for multiple point lenses are given by Walters & Forbes (2017). When finite-source effects are relevant

but sufficiently weak (e.g. caustic or cusp passages without caustic crossing), multipole approximations result in computation times orders of magnitude faster than the exact finite-source magnification (Pejcha & Heyrovský, 2009). Quadrupole and hexadecapole approximations employ 9 and 13 (point source) resolution of the polynomial lens equation to evaluate the corresponding expansion coefficients (Gould, 2008; Cassan, 2017).

### 5.3.7 High-magnification events

In early studies of planetary microlensing, it was expected that the identification and analysis of magnification patterns of the planetary caustics, of the sort evident in Figure 5.8, would offer the best prospects of detection planetary signals (e.g. Gould & Loeb, 1992). But such events are of typically rather low magnification, and therefore less easy to detect, and less easy to observe photometrically with adequate signal-to-noise.

Griest & Safizadeh (1998) demonstrated that there are advantages in concentrating searches around the central stellar caustic: large deviations from the single lens light curve can still occur due to the presence of a planet, and the high magnification (and the more accurate photometry therefore possible) should make these changes in the central caustic structure detectable.

This can be visualised with reference to Figure 5.2: near the peak of high-magnification point-lens events, the two images created by the primary lens are highly magnified and distorted, and the combined image pattern reaches its closest manifestation of an Einstein ring. The two images sweep around opposite sides of the Einstein ring, together probing almost  $2\pi$  rad, with the resulting total magnification extremely sensitive to small planetary companions close to the Einstein radius (and to larger planets at larger separations). As a result, planets over a broad range of separation and position angle will create a caustic that will perturb the light curve.

The low magnification wings may also provide evidence for, or place limits on, the existence of accompanying close-in planets such as habitable Earths or hot Jupiters (Di Stefano, 2012a; Abe et al., 2013a). Further investigations of the characteristics of high-magnification events are reported by Chung et al. (2012).

**Observations** Although events of high magnification ( $A \geq 100$ ) are rare, the combined OGLE and MOA surveys (§5.9) are now discovering some 600–1000 microlensing events towards the Galactic bulge each year, with a few very high magnification events amongst them.

Focusing on high magnification events has a number of advantages: only relatively sparse temporal monitoring by the survey groups (one or two times per night) is required to predict their occurrence well in advance of maximum, thereby allowing observations to be concentrated on potentially important events as they unfold

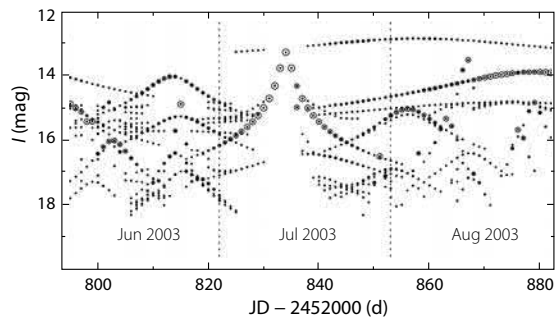


Figure 5.9: Sampling of 443 OGLE events between 2003 June–August, optimised for a 2-m telescope with total observing time 1.5 h per night. Circles are proportional to the allocated time, chosen to maximise total planet detectability. Too many targets implies high telescope slew time, while too few is inefficient because the detection zone areas grow as  $t^{1/2}$ . On some nights, one high-magnification event may be the only priority. From Horne et al. (2009, Figure 12), © Oxford University Press.

(see Figure 5.9). They are particularly well suited for the detection of multiple planets, since they automatically probe the region of the central caustic, where even low-mass planets sufficiently near the Einstein ring will further perturb the light curve (Bond et al., 2002a; Rattenbury et al., 2002; Abe et al., 2004; Ryu et al., 2011).

Their brightness also means that they are accessible to observation by small telescopes (to which amateurs are now contributing), and since the sources are consequently typically very faint, it is easier to characterise the planetary host star with follow-up observations less perturbed by source blending.

Several events with  $A \gtrsim 800$  have been reported. At these levels, a source of (say)  $I = 20$  mag would be temporarily magnified to reach  $I \approx 13$  mag. The highest magnification reported to date is  $\sim 3000$  in the case of OGLE-2004-BLG-343 (Dong et al., 2006).

### 5.3.8 Short-duration events

Although  $t_E \propto M_L^{0.5}$  (Equation 5.18) the event time scale is a poor proxy for the lens mass because, even at fixed lens mass  $M_L$  and source distance  $D_S$ , the large range of lens distances and lens–source relative velocities results in a large range of possible time scales.

Instead, short-duration events are likely to comprise planetary mass objects (free-floating or bound); rapidly moving stellar mass objects such as neutron stars, halo stars, runaway stars, or hypervelocity stars; or events with small lens–source separation (Di Stefano, 2012b,c).

As emphasised by Di Stefano (2012b), for any given lens mass and velocity, events of short duration are preferentially caused by nearby lenses (mesolenses, §5.8), or by lenses so close to the source star that finite source-size effects may be detected. Planets causing short-duration events may be in orbits with any orientation, and with a broad range of mass and semi-major axis.

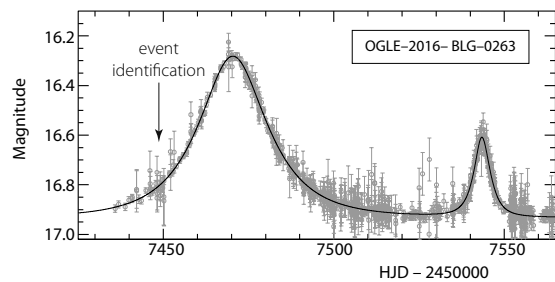


Figure 5.10: The ‘repeating event’ light curve of OGLE-2016-BLG-0263. The curve superposed on the data points represents the best-fit binary-lens model. The arrow denotes the time when the event was first discovered. The original colour figure distinguishes data points from the OGLE, MAO, and KMTNet (CTIO, SAAO and SSO) high-cadence surveys. From Han et al. (2017c, Figure 1), by permission of IOP Publishing/AAS.

### 5.3.9 Repeating events

The term *repeating event* has been used to describe lensing geometries in which enhanced magnification of two or more lensing events are well separated. These may occur when the projected separation of a 2-point lens is substantially larger than  $R_E$ , and the source trajectory passes the effective magnification regions of both primary and planet (case b in Figure 5.5).

For example, in OGLE-2015-BLG-263L (Han et al., 2017c), the companion produced its own single-mass light curve after the event produced by the primary had ended (Figure 5.10). A qualitatively similar repeating event could also result from source binarity, excluded in the case of OGLE-2015-BLG-263L through continuous coverage of the second peak.

A planet with a binary lens whose orbital period is comparable to the event duration could yield repeating quasi-periodic features as the source traverses the same regions in the rotating lens plane (Guo et al., 2015).

### 5.3.10 Binary lens, binary source

The first planetary microlensing event attributed to a binary source star, viz. a binary source, binary lens event, was MOA-2010-BLG-117 (Bennett et al., 2018). A strong microlensing parallax signal yields  $M_\star = 0.58 \pm 0.10 M_\odot$ , with  $M_p = 0.51 \pm 0.07 M_J$  at  $a \sim 2.9$  au, the system therefore resembling a half-scale model of the Sun–Jupiter system. The source stars are slightly evolved, and by requiring them to lie on the same isochrone, the source is constrained to lie in the near side of the bulge at  $D_S = 6.8 \pm 0.6$  kpc, with an implied  $D_L = 3.4 \pm 0.2$  kpc.

### 5.3.11 Free-floating objects

While most sensitive to planets with projected separations close to  $\theta_E$ , microlensing should also be capable of detecting much wider separation, or even ‘free-floating’ planet-mass bodies. Although the detection probability

decreases for increasing separations because of the decreasing magnification of the major image, it does not drop to zero even for arbitrarily large separations. For events in which the primary star is also detected, the detection probability for very wide planets with  $d \gg 1$  is  $\propto d^{-1}$  (Di Stefano & Scalzo, 1999b).

Even if a host star event is absent or undetected, wide separation or free-floating planets can be detected if they give rise to isolated, short-term events (Di Stefano & Scalzo, 1999a; Han et al., 2005). These could include objects at the low end of the star-formation mass function (§9.9), as well as planets ejected from their host system by planet–planet interactions. Statistics should provide further constraints on this aspect of planet formation and evolution (Ban et al., 2016; Ma et al., 2016b). The gravitational mass of nearby free-floating planet-mass lenses could be determined by combining the photometric lensing light curve with deep images that detect the planet itself (Di Stefano, 2012b). Evidence for such a population is discussed in §5.10.2.

Han et al. (2004) discussed mass determination using extended baselines (§5.5.5). Han (2006b) showed that a degeneracy between isolated events and wide-separation planets could be distinguished through astrometric microlensing follow-up, given its larger cross section (§5.8). Observing strategies to optimise their detection, including with K2, Euclid and WFIRST (§5.9.5), have been considered (Gould & Yee, 2013; Ryu et al., 2013; Hamolli et al., 2015; Gould, 2016a; Henderson & Shvartzvald, 2016).

### 5.3.12 Planets orbiting a binary system

Detectability of planets orbiting binary stars by microlensing was first studied by Han (2008b). For  $M_p \sim 1M_J$ , high detection efficiency is expected for orbits in the range 1–5 au around binary stars with separations 0.15–0.5 au. Lee et al. (2008) showed that in configurations where a planet orbits one of the binary components (and the other binary component is located at a large distance), both planet and secondary produce perturbations in a common region around the planet-hosting component. Signatures of both planet and binary companion may therefore be detectable in the light curves of high-magnification events.

Of the microlensing planetary systems detected to date, there are two cases of a binary star with an orbiting planet, one being a circumprimary, and one being a circumbinary.

OGLE–2008–BLG–92L is a binary stellar system with a circumprimary Uranus-mass planet (Poleski et al., 2014a). It was discovered in 2008 as a planetary event followed by the primary event (with respective peaks separated by 186 d), with a further event at the same position nearly two years later attributed to a low mass star or brown dwarf secondary (Figure 5.28).

OGLE–2007–BLG–349L(AB) is a circumbinary planetary system, with a planet of mass  $80 \pm 13M_\oplus$  orbiting a pair of M dwarfs with masses of  $0.41 \pm 0.07$  and  $0.30 \pm 0.07M_\odot$  (Bennett et al., 2016).

**Triple lens critical curves and caustics** In addition to these triple lens systems comprising two stars and one planet, there are two cases of a single star with two planets (OGLE–2006–BLG–109L and OGLE–2012–BLG–26L). Other, as yet undetected, types of triple lenses include triple stars, or stars with a planet with a moon. Daněk & Heyrovský (2015) give analytical and numerical methods for mapping the critical-curve topology and caustic cusp number for a subset of triple-lens configurations, and find various unusual structures of primary and secondary caustic loops.

## 5.4 Light curve modeling

### 5.4.1 Ray shooting

For a binary or multiple lens system, the lens equation is a generalisation of Equation 5.4, in which the observer, source, and lens system no longer necessarily lie in a single plane. Although mapping from the image to source plane for an arbitrary lensing geometry can be simply formulated (e.g. in complex coordinates: Bourassa et al., 1973; Witt, 1990; Bennett & Rhie, 1996; Griest & Safizadeh, 1998), solving directly for all possible images and their total magnification for realistic configurations is generally impractical.

An alternative is to exploit the simplicity of the mapping from image to source plane in a technique originally developed by Kayser et al. (1986) and Schneider & Weiss (1987) to study the effects of microlensing in the variability of active galactic nuclei, and referred to as *ray shooting* (or equivalently as *inverse ray shooting*, because in practice the photon paths are modeled ‘backwards’ from the observer in the direction of the lens, and hence to the source plane).

In the approach described by Wambsganss (1997), representative binary lens magnification maps are generated for trial values of  $q$  and  $d$  by propagating a uniform bundle of light rays backwards from the observer, through the lens plane containing star and planet, and collected in the source plane. The density of rays at a particular location in the source plane is then proportional to the magnification at that point. Light curves at arbitrary trajectory angles  $\alpha$  can be obtained from appropriate one-dimensional cuts through such a magnification pattern, convolved with the source profile.

Early examples of magnification maps and light curves were given by Gould & Loeb (1992), Wambsganss (1997), and Gaudi & Sackett (2000). Conceptually, an observed microlensing event could then be interpreted by comparison with a (huge) library of such magnification maps and light curves to infer the lensing geometry.

### 5.4.2 Model fitting

Practical detection and model fitting typically follows a numerical approach to establish the detailed lensing geometry (e.g. Gould et al., 2006b). The aim is to characterise a given exoplanet light curve on the basis of seven numerical parameters: the three single-lens geometric parameters ( $t_0, u_0, t_E$ ), the three binary lens parameters ( $q, d, \alpha$ ), and a seventh ( $\rho \equiv \theta_\star / \theta_E$ ) which is required whenever the angular radius of the source  $\theta_\star$  plays a significant role in the fine structure of the light curve, in particular when the source crosses a caustic (§5.5).

For planetary lenses with (high magnification) caustic crossings there are seven observable light curve features that directly constrain the model parameters, up to the two-fold degeneracy  $d \leftrightarrow d^{-1}$  (Dominik, 1999). Three of these, the epoch, peak and duration of the primary lensing event strongly constrain  $t_0, u_0$  and  $t_E$  respectively, and these values can be used as seeds. The entry and exit caustic crossing times, and the height and duration of (one of) the caustic crossings, then constrain  $(d, q, \alpha, \rho)$ . Model values are extracted by a numerical grid search of parameter space, typically by holding  $(d, \alpha, q)$  fixed at a set of values while minimising  $\chi^2$  over the remaining four parameters (e.g. Bennett, 2010).

Modeling is computationally intensive, with the globally-best model often hard to find because of the many local minima, and with some events requiring tens of thousands of processor hours to model (Gould, 2008; Bate et al., 2010b; Bozza, 2010; Walters & Forbes, 2011; Penny, 2014; Zhu et al., 2014a). Implementation on GPU hardware has been reported (McDougall & Albrow, 2016). Interpretation of the more complex light curves often proceeds with collaborating groups using independent methods to corroborate the results.

Brown (2014b) has proposed an alternative discovery approach, formulated in the context of the WFIRST and Euclid space missions (§5.9.5), and aiming to reach lower detection thresholds. It employs the statistical concept of ‘energy detection’ to quantify the presence of a deterministic signal irrespective of its shape.

While including additional planets may formally improve the model fits, data systematics have proven to be a limiting factor in practice (Shin et al., 2015).

**Algorithms** Various modeling software is publicly available (detailed at microlensing-source.org, see Table 1.4), including pyLIMA (Bachelet et al., 2017), VBBinaryLensing (Bozza, 2010), MuLensModel (Poleski & Yee, 2018), and muLAn.

### 5.4.3 Lens–source transverse motion

The relative lens–source transverse motion,  $v_\perp$ , which drives the rapidly changing magnification during a microlensing event, cannot be determined uniquely from the microlensing light curve alone. Estimates may

be possible, long after the microlensing event, from accurate astrometry, or from measurements of the image elongation, or from the colour-dependent centroid shift using, for example, the very stable point-spread function of HST. Measurement of the relative source–lens angular proper motion,  $\mu_{LS}$ , can then establish the angular Einstein radius via Equation 5.19, and hence  $M_L$  as a function of  $D_L$  from Equation 5.6. Events in which such effects have been observed are noted in §5.10.1.

## 5.5 Higher-order effects

Various other higher-order effects are relevant for the modeling and interpretation of planetary lensing events. These include the finite angular size of the source, limb darkening of the source star, blending of the source and/or lens images, effects of orbital motion (of the lens system, of the Earth, or of the source star), and the dependence on measurement baseline.

### 5.5.1 Blending

The dense star fields of the bulge have typical angular separations much smaller than the seeing disk, and the flux of other stars frequently contributes to the measured light curve. Such *blending* can be due to a physical source star companion, due to the lens, or due to the superposition of another (non-lensing) object along the line-of-sight, introducing further complexity and degeneracy in the fitting (Alard, 1997; Wozniak & Paczyński, 1997; Alard & Lupton, 1998; Gould & An, 2002).

Separation between light from the source star and the (normally unrecognisable) blended contribution of light from the lens may be possible once the angular separation between source and lens has increased to a few milliarcsec, perhaps several years after the microlensing event occurred (Bennett et al., 2007; Gould et al., 2010a). Any difference in colour between source and lens will result in a (small) displacement in the image centroid as a function of wavelength. Measurement of the centroid shift from multicolour high-angular resolution imaging may then provide an estimate of the host star spectral type and, with some further assumptions on the underlying stellar population, an estimate of  $D_L$ , and hence a complete solution of the lens equation.

The effect was detected for the first microlensing planet OGLE-2003-BLG-235 in HST observations made 1.8 years after peak magnification, when the lens–source separation was  $\sim 6$  mas (Bennett et al., 2006).

### 5.5.2 Finite source size

During high magnification events with small values of the projected lens–source separation, the finite angular diameter of the source means that different regions of its stellar disk are magnified at different times during the

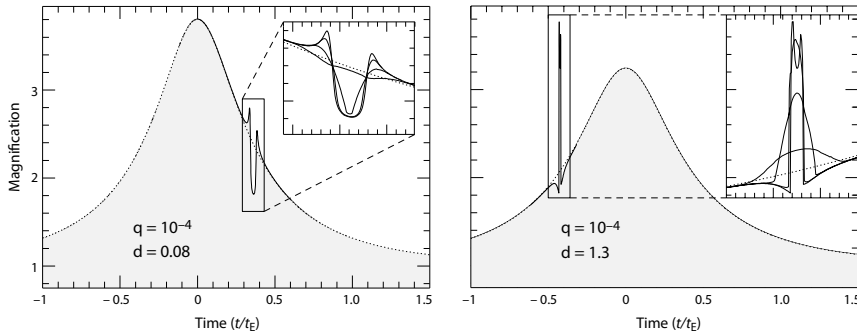


Figure 5.11: Theoretical microlensing light curves showing planetary deviations for a binary lens of mass ratio  $q = 10^{-4}$ , and two values of  $d$ . Dashed curves are for an unperturbed single lens. The main plots are for a stellar radius  $\rho = 0.003$ , with the insets showing the progressively smaller amplitudes for larger stellar radii ( $\rho = 0.006, 0.013, 0.03$ ). From Bennett & Rhie (1996, Figure 1), by permission of IOP Publishing/AAS.

event, such that distinctive finite source size effects may be evident. Since at high magnification  $A \approx 1/u$  (Equation 5.15), taking representative values of  $\theta_E \sim 1$  mas (Equation 5.5) and  $\theta_\star \sim 1 \mu\text{as}$ , suggests that such effects should be expected for  $A \gtrsim 1000$ .

Detailed effects have been calculated for various configurations (Bennett & Rhie, 1996; Han et al., 2005; Chung & Lee, 2011a). Examples for a planet mass ratio  $q = 10^{-4}$ , and for a range of values of the parameter  $\rho = \theta_\star/\theta_E$ , are shown in Figure 5.11. Planet-induced deviations become less pronounced for larger  $\theta_\star$ , reaching detectability limits at  $\rho \sim 0.03$ . For main sequence source stars,  $R \sim R_\odot$ , finite source effects become important for  $M_p \sim 1M_\oplus$  (Bennett & Rhie, 1996; Jung et al., 2014), and render them undetectable below  $M_p \sim 0.02M_\oplus \sim 2M_{\text{Moon}}$ . For bulge clump giants, finite source effects preclude planet detection for  $M_p \lesssim 5M_\oplus$ .

Good precision can be achieved in practice. Dong et al. (2009a) determined  $\rho = (3.29 \pm 0.08) \times 10^{-3}$  for the planetary event MOA-2007-BLG-400.

If the source star is visible and unblended, its angular radius  $\theta_\star$  can be estimated from the angular size–colour relation based on its (extinction-corrected) magnitude and colour (Yoo et al., 2004b). With the source radius crossing time,  $t_\star$ , derived from the microlensing light curve, the angular Einstein radius follows from

$$\theta_E = \frac{\theta_\star t_E}{t_\star}. \quad (5.32)$$

The dependency of  $M_L$  on  $D_L$  (whether known or not) follows from Equation 5.6, while the linear projected star–planet separation, and hence a lower limit on the size of the exoplanet orbit, follows from the value of  $d$ .

**Hollywood events** Gould (1997b) emphasised the advantages of monitoring events with giant-star sources, being both brighter (easier to monitor) and bigger (thus with the prospect of measuring an additional parameter

from finite-source effects, viz. the proper motion). This approach of following the ‘big stars’ was described as the ‘Hollywood strategy’. The high perturbation ( $\Delta\chi^2 \sim 10000$ ) ‘Hollywood event’, OGLE-2017-BLG-173, results from a large bright source passing over and enveloping the planetary caustic (Hwang et al., 2018b).

### 5.5.3 Limb darkening of the source

Associated with the effects of finite source size is the possibility of a detailed modeling of limb darkening for the source star, since in practice the surface brightness of its stellar disk varies with radius. Modeling of  $\rho$  may proceed on the assumption of a uniform stellar disk, or by using a more physically appropriate radial surface brightness profile. An improved measurement of stellar limb darkening may be obtained as a by-product of a more detailed model of these finite source effects.

Limb darkening was first modeled for the non-planetary events MACHO-1997-BLG-28 by Albrow et al. (1999), and subsequently for MACHO-1997-BLG-41 (Albrow et al., 2000a), OGLE-1999-BLG-23 (Albrow et al., 2001b), and others. A detailed profile, inconsistent with current atmospheric models, was obtained for the K giant event EROS-2000-BLG-5 by Fields et al. (2003). Such an analysis for the  $H$ -band photometry in the planetary microlensing event MOA-2007-BLG-400 (Dong et al., 2009a), and with  $I$  and  $R$ -band for OGLE-2004-BLG-482 (Zub et al., 2011) nevertheless showed good agreement with the models of Claret (2000).

### 5.5.4 Orbital motion

Three distinct orbital effects can modify the rectilinear geometry of the observer–lens–source alignment: orbital motion of the lens, orbital motion of the observer, and orbital motion of the source.

Dominik (1998) investigated the effects of a (short-period) rotating binary lens, a rotating binary source,



and a rotating observer (Earth orbiting the Sun), finding that the most dramatic effects are for the former, since the caustic structure itself changes with time. This rotation introduces five additional parameters: two rotation angles, the binary period, the eccentricity and phase.

**Excluding a stellar mass binary lens** Effects attributed to an exoplanet must exclude other time-dependent phenomena as a cause of any fine structure in the light curve, and in particular the orbital motion of a binary lens where both components have stellar masses. Binary lenses both of stellar mass have been reported in a few cases where the light curve contains well-measured caustic crossings that establish key times in the orbit to  $\sim 10^{-5} t_E$ . Indeed, the first claimed planetary microlensing event MACHO-97-BLG-41 (Bennett et al., 1999) was revised when an improved fit was found invoking a binary with  $P_{\text{orb}} = 1.5$  yr (Albrow et al., 2000a). Similarly, modeling of EROS-2000-BLG-5 required inclusion of finite source effects, microlens parallax, and binary orbital motion (An et al., 2002).

A planet with a binary lens whose orbital period is comparable to the event duration could yield repeating quasi-periodic features as the source traverses the same regions in the rotating lens plane (Guo et al., 2015).

**Orbital motion of a star-planet lens** The possibility of detecting orbital motion of a planet around the host star, due to the changing shape and position of the caustics with time, was discussed by Bennett (2008), who reasoned that the effect could be detected for planetary events lasting  $\Delta t = 1 - 10$  d, if shifts in the lens position with respect to the source could be detected at levels of  $\sim 0.1 \theta_* / \theta_E$ . Since the microlensing planet signal is only evident for 5–50 d, much less than the likely orbital period of 5–10 yr, it is typically sufficient to consider the lowest order components of orbital motion, viz. the 2d relative velocity in the plane of the sky. More detailed studies consider both separational and rotational events (Penny et al., 2011).

The effect was first seen for planetary mass lens companions for the outer planet in the first multiple planetary microlensing event, OGLE-2006-BLG-109L (Gaudi et al., 2008). As discussed further in §5.10.1, orbital motion changes the projection geometry of the planetary caustic, leading to both its rotation and change of shape during the event. Although orbital periods are likely to be long (several years), and the peak microlensing events last only several days, the caustic size is  $\propto 1/|d-1|$ . For OGLE-2006-BLG-109,  $d = 1.04$ , implying that a change in projected orbital separation of 0.5% over the eight days between the first cusp crossing and the peak gave a measurable 10% change in caustic size. The components of the projected velocity of the planet relative to the primary star, together with the stellar mass, determine the outer planet's orbit (including inclination) on the assumption that it is circular.

Orbital motion was also seen in the long-duration event ( $t_E = 44.3$  d) MOA-2010-BLG-73L (Street et al., 2013).

**Orbital motion of the observer** The orbital motion of the Earth during a lensing event implies that the lens does not appear to move at a constant velocity with respect to the source, as seen by an Earth-based observer. This (orbital) microlens parallax effect can in principle be detected for events with time scales  $t_E \gtrsim 10 - 50$  d, and can lead to a direct determination of the lens mass. It is discussed further in §5.5.5.

**Orbital motion of the source** In some 10% of cases where the source is a binary, the effect of orbital motion can cause similar light curve distortions to the parallax effect. Viewed as the

converse of the parallax effect, it has been referred to as the *xallarap* effect (Bennett, 1998; Furusawa et al., 2013).

### 5.5.5 Parallax and lens mass

The *microlens parallax*,  $\varpi_E$ , is defined as the lens–source relative parallax,  $\varpi_{\text{rel}}$ , scaled to the angular Einstein radius  $\theta_E$  (Gould, 1992, 2004)

$$\varpi_E = \frac{\varpi_{\text{rel}}}{\theta_E}. \quad (5.33)$$

Its significance is that the lens mass can be determined if both  $\varpi_E$  and  $\theta_E$  can be measured. The lens distance also follows if an estimate of the source distance is available.

In the expression for the angular separation between the lens and source (Equation 5.24), the observer, lens, and source are assumed to be moving with constant velocity. There is also an implicit assumption that the values of  $t_0$ ,  $u_0$ , and  $t_E$  are constant. Effects due to microlens parallax occur when the observer(s) are not copatial or nonaccelerating.

Measurements of  $\varpi_E$  can therefore be made by exploiting the non-linear (orbital) motion of the Earth around the Sun, or by making simultaneous observations of the microlensing light curve over an extended measurement baseline.

**Formulation** In Figure 5.12, corresponding to the geometry of Figure 5.1, the impact parameter is set to the physical size of the (linear) Einstein radius, such that the corresponding deflection angle  $\alpha_E = 4GM_L/(c^2 R_E)$ . The undeviated ray is propagated onwards to the observer plane to define a projected value of the Einstein radius,  $R'_E$ . From trigonometry (and for small angles),  $R'_E = \alpha_E D_L$  and  $R_E = \theta_E D_L$  which, using the deflection expression for  $\alpha_E$  gives

$$\theta_E R'_E = \frac{4GM_L}{c^2}. \quad (5.34)$$

Also, from angular equalities

$$\theta_E = \frac{R'_E}{D_L} - \frac{R'_E}{D_S} = R'_E \left( \frac{1}{D_L} - \frac{1}{D_S} \right) = \frac{\varpi_{\text{rel}}}{\text{au}} R'_E, \quad (5.35)$$

where the relative parallax,  $\varpi_{\text{rel}}$ , has an amplitude

$$\varpi_{\text{rel}} = \text{au} \left( \frac{1}{D_L} - \frac{1}{D_S} \right) = \text{au} \left( \frac{D_{LS}}{D_L D_S} \right), \quad (5.36)$$

where  $\varpi_{\text{rel}}$  is in radians, and  $D$  (defined in §5.2) and the au (astronomical unit) are in common units.

By analogy with the usual trigonometric parallax  $\varpi = \text{au}/d$  (where  $\varpi$  is in rad for a distance  $d$  in au or, alternatively, au and  $d$  are in common units), the microlens parallax expresses the size of the Earth orbit relative to the Einstein radius of the microlensing event projected onto the observer plane

$$\varpi_E = \frac{\text{au}}{R'_E}. \quad (5.37)$$

Equations 5.34–5.37 can be rearranged to give

$$M_L = \frac{\theta_E}{\kappa \varpi_E}, \quad (5.38)$$

$$\varpi_E = \sqrt{\frac{\varpi_{\text{rel}}}{\kappa M_L}}, \quad (5.39)$$

$$\theta_E = \sqrt{\kappa M_L \varpi_{\text{rel}}}, \quad \text{and} \quad (5.40)$$

$$\varpi_{\text{rel}} = \theta_E \varpi_E, \quad (5.41)$$

where  $\kappa = 4G/(c^2 \text{au}) \sim (8.1/M_\odot)$  mas.

For microlensing events the (measured) Einstein time is related to the (unknown) lens–source relative proper motion according to Equation 5.19. With  $\theta_E$  given by Equation 5.40, it follows that determination of  $\varpi_E$  would eliminate uncertainty arising from the unknown relative proper motion, and would give a direct relation between  $M_L$  and  $\varpi_{\text{rel}}$  through Equation 5.39.

If both  $\theta_E$  and  $\varpi_E$  (or equivalently  $R'_E$ ) can be determined, then the lens (host star) mass can be established from Equation 5.38 (and the planet mass thereafter from the mass ratio,  $q$ ), and the lens–source relative parallax from Equation 5.41. This provides a distance to the event, and hence the linear size of the projected star–planet separation, if the distance to the background source can be estimated.

**Observations exploiting Earth's orbital motion** Experimentally,  $\varpi_E$  can be determined from the acceleration of the Earth's orbital motion around the Sun. For microlensing events with suitably long Einstein crossing times, the resulting departure from rectilinear relative motion between observer–lens–source results in a correspondingly distorted light curve.

This way to estimate  $\varpi_E$  was proposed in the context of MACHO microlensing searches by Gould (1992), and developed by Smith et al. (2003). Alcock et al. (1995) used it to place the first constraints on a lens mass and distance, An et al. (2002) determined the lens mass for the microlensing binary EROS–2000–BLG–5, and the same principle has been applied to other events subsequently. Nevertheless the effect remains only occasionally detectable: Smith et al. (2002) found just one in a search of 512 microlensing candidates during 1997–99, while Poindexter et al. (2005) found just 22 events (out of  $\sim 3000$ ) for which inclusion of the effect significantly improved the light curve fit.

The method was first applied, to a planet event, to determine the host star mass for the high-magnification event OGLE–2006–BLG–109 (Gaudi et al., 2008).

#### Observations over extended (Earth–satellite) baselines

For a microlensing event observed simultaneously at two locations separated by a distance of order  $R_E \sim 1$  au, both the impact parameter and the time of maximum magnification will differ. Comparison of the light curves of these different alignment geometries allows a more direct estimate of  $\varpi_E$  to be made.

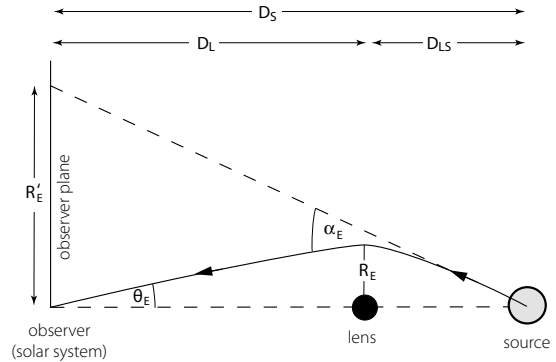


Figure 5.12: Schematic of light bending for impact parameter  $b = R_E$ . The linear Einstein radius  $R_E$  in the lens plane subtended at the source, projects to a scaled value at the solar system  $R'_E$ . Determination of the microlens parallax can be made from measurements of the microlensing light curve from widely spaced locations in the observer plane.

Refsdal (1966) proposed that the effect could be detected, and the primary lens mass determined, by observations made simultaneously from Earth and from a distant space observatory, ideas which have been developed subsequently, notably in the context of Spitzer and Kepler (Gould, 1992; Boutreux & Gould, 1996; Gould et al., 2003b; Gould & Yee, 2012; Gould, 2013a; Gould & Horne, 2013a; Gould & Yee, 2014; Yee et al., 2015a; Yee, 2015; Zhu et al., 2015a; Calchi Novati & Scarpetta, 2016; Mogavero & Beaulieu, 2016; Lee, 2017).

In the first practical application, although not for a planetary system, Dong et al. (2007) combined ground-based and Spitzer observations to measure the microlens parallax of OGLE–2005–SMC–001. Their solution defined a lens geometry with an eightfold degeneracy (two each for parallax, binary separation, and cusp approaches) but led to a parallax measurement (Figure 5.13) yielding a projected transverse lens velocity of  $230 \text{ km s}^{-1}$ , a typical value expected for halo lenses, but excluding the possibility that the lens was in the Small Magellanic Cloud itself.

Various measurements by Spitzer giving a geometric measure of the lens mass have since been reported: for the planetary systems OGLE–2014–BLG–124L (Udalski et al., 2015b, see Figure 5.14), for the caustic crossing binary system OGLE–2014–BLG–1050L (Zhu et al., 2015b), for the isolated lens OGLE–2014–BLG–939 (Yee et al., 2015b), for 21 further isolated lenses (Calchi Novati et al., 2015), for OGLE–2015–BLG–448 (Poleski et al., 2016), and for the cold Neptune OGLE–2015–BLG–966 (Street et al., 2016).

The almost equal mass M dwarf binary lens OGLE–2016–BLG–168 (Shin et al., 2017), although not hosting a planet, further illustrates the change in perspective and model constraints provided by combined ground and space-based observations (Figure 5.15).

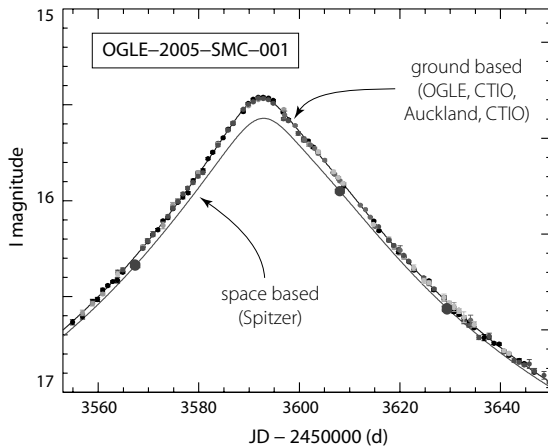


Figure 5.13: Light curve of the microlensing event OGLE-2005-SMC-001 observed simultaneously from ground (upper curve), with a separate fit using photometry from the Spitzer space telescope (lower curve). The model includes two additional parameters to account for binary rotation, and two further parameters to account for the microlens parallax. From Dong et al. (2007, Figure 4), by permission of IOP Publishing/AAS.

Microlens parallax measurement from simultaneous observations between the Kepler spacecraft and Earth was the objective of the K2 Campaign 9, between 2016 April 22 to July 1 (Gould & Horne, 2013b; Henderson et al., 2016; Hamolli et al., 2017; Penny et al., 2017). Specific challenges in the data analysis are posed by the crowded field and spacecraft pointing characteristics (Zhu et al., 2017a).

The (non-planetary) event MOA-2016-BLG-290 was the first observed from three well-separated ( $\sim 1$  au) locations: Earth, Spitzer, and Kepler/K2 (Zhu et al., 2017c).

**Observations over terrestrial baselines** From the consideration of photon statistics, Holz & Wald (1996) argued that microlens parallaxes could theoretically be measured even from a much smaller baseline, specifically using two widely-spaced observatories on Earth. Gould (1997a) showed that for events of very high magnification, and for observers separated by  $\sim 1R_{\oplus}$ , the size of the effect is  $\sim A_{\max}R_{\oplus}/R_{\oplus}'$ , and can be of order 1%.

Such observations were made for the first time for the thick disk brown dwarf OGLE-2007-BLG-224 (Gould et al., 2009), for the  $A = 1600$  event OGLE-2008-BLG-279 (Yee et al., 2009), and for the candidate planetary event MOA-2011-BLG-274 (Freeman et al., 2015).

### 5.5.6 High-resolution imaging

In addition to follow-up space observations of lensing events, Cassan & Ranc (2016) detailed the physical constraints which could be provided by long-baseline optical interferometry (§7.6.5). They estimated that a few events per year are already within reach of CHARA or

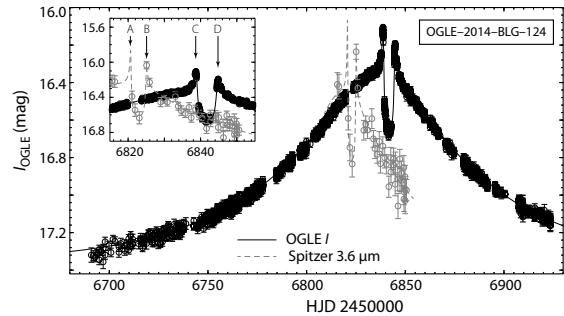


Figure 5.14: Light curve of OGLE-2014-BLG-124 observed from Earth by OGLE in the I band, and by Spitzer at  $3.6\mu\text{m}$ . The Spitzer satellite was located  $\sim 1$  au west of Earth (in projection) at the time of the observations. Spitzer observed similar features attributable to this Jupiter mass planet 20 d earlier, demonstrating a (projected) lens motion of  $105\text{ km s}^{-1}$  due east. In the main diagram only, the Spitzer light curve is displaced by 0.2 mag for clarity. From Udalski et al. (2015b, Figure 2), by permission of IOP Publishing/AAS.

VLTI observations reaching  $K \sim 10$  mag, with an order of magnitude more for a limit  $K \sim 11$  mag.

Similarly, ‘lucky imaging’ (§7.3.2) could reduce the blending effect and lead to increased detection efficiencies (Rahvar, 2016a; Sajadian et al., 2016).

## 5.6 Potentially observable effects

This section summarises a variety of other related effects that might be observable in the future.

### 5.6.1 Structure in the lens

*Finite lens size:* Astrometric effects due to finite lens size have been considered by Takahashi (2003) and Lee et al. (2010c).

*Planetesimal disks and asteroid belts:* Disks around the lensing planet of nearby stars, even several orders of magnitude below Earth mass, may result in light curves exhibiting short-term low-amplitude residuals (Heng & Keeton, 2009; Hundertmark et al., 2009). Similar signatures from asteroid belts, resulting in ‘pseudo-caustics’ and discontinuities in magnification, may be detectable (Lake & Zheng, 2017; Lake et al., 2017).

*Satellites of the lensing planet:* The detection of planetary satellites associated with the foreground lens, due to the changing magnification patterns, is considered problematic due to finite source effects (Han & Han, 2002). For the specific case of Earth-mass satellites orbiting ice-giant planets, Han (2008a) found that non-negligible satellite signals might occur when the planet-satellite separation is similar to or greater than the Einstein radius of the planet, thus for projected separations of 0.05–0.24 au for a Jupiter-mass planet.

Liebig & Wambsganss (2010) made extensive triple-lens simulations over a range of two-dimensional projections of the three body configurations, and also concluded that the detection of planetary satellites is feasible under favourable configurations (Figure 5.16). Simulations for a satellite orbiting a wide separation planet were also made by Chung & Ryu (2016).

*Three-dimensional microlensing:* This term has been used to describe the occurrence of two lenses at different distances

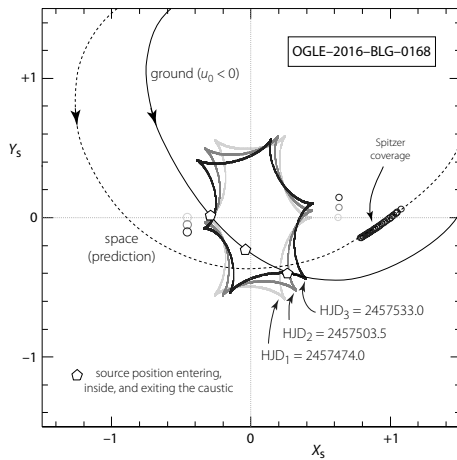


Figure 5.15: The (almost equal mass)  $M$  dwarf binary microlensing event OGLE-2016-BLG-168, showing caustic features reflecting the orbital motion of the lens system as the source enters, is inside, and exits the caustic; the source position at those times is indicated (no planet accompanies this system). The solid line is the source trajectory from ground-based models. The dashed line is the predicted source trajectory of the Spitzer light curve based on those models, here for  $u_0 < 0$ . From Shin et al. (2017, Figure 2a), by permission of IOP Publishing/AAS.

along the line-of-sight (Mao et al., 2014). Light curves can be qualitatively different from lensing in a single plane, although the probability of such a configuration being observed, even towards the Galactic centre, is very small.

**Timing analysis:** Timing analyses applied to the orbital period of binary lenses, and to the rotation period of the lensed star due to star spots, is considered by Giordano et al. (2017).

### 5.6.2 Structure in the source

**Binary source:** The first star-planet microlensing event attributed to a binary source was MOA-2010-BLG-117 (Bennett et al., 2018), detailed in §5.3.10. The results suggest that further structural insights into the source should be possible. A binary source interpretation for the binary lens system OGLE-2016-BLG-0733 is discussed by Jung et al. (2017, Section 3.2).

**Satellites, rings, and atmospheres:** Essentially all discussions of planetary microlensing focus on planets around the (foreground) lens star. But planets might also be detected in the source plane as they cross the caustics of the foreground lens, while reflected light from a planet may contain information on its atmosphere, or the presence of satellites or rings. Such structure may be subject to substantially higher magnification than a uniformly illuminated disk (Heyrovsky & Loeb, 1997; Minniti et al., 1998; Gaudi & Gould, 1999; Graff & Gaudi, 2000; Lewis & Ibata, 2000; Heyrovsky et al., 2000; Ashton & Lewis, 2001; Gaudi et al., 2003; Sajadian & Rahvar, 2010). Expressing the magnitude of the deviation as

$$\delta_p \sim \epsilon_p \rho_p^{-1/2}, \quad (5.42)$$

where  $\epsilon_p$  is the fraction of reflected starlight and  $\rho_p$  is its angular radius (in units of the angular Einstein ring radius), Gaudi et al. (2003) found that rings produce deviations of the order of  $0.1\delta_p$ , whereas satellites, spots, and zonal bands produce

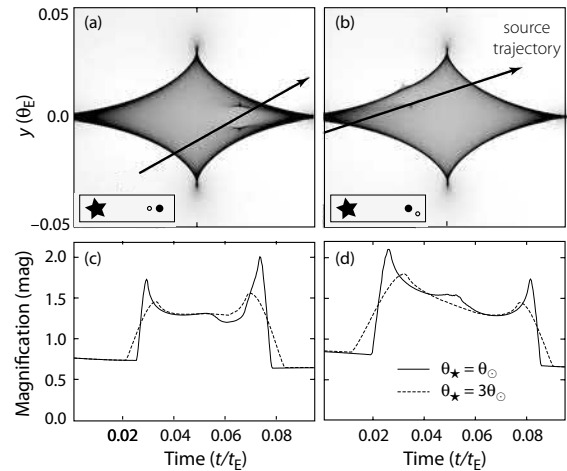


Figure 5.16: Microlensing detectability of planetary satellites, showing two configurations of triple-lens geometries, in which the satellite has moved in its orbit by  $210^\circ$  between the two. Mass ratios are  $q = 10^{-3}$  and  $10^{-2}$  for the planet-star and satellite-planet. Angular separations are  $1.3\theta_\odot$  (star) and  $1.3\theta_\odot$  (planet). Top: magnification maps (darker regions are higher magnification), with the geometrical configurations shown at bottom left. Bottom: light curves for the source trajectories indicated. Solid and dashed curves correspond to angular source sizes of  $\theta_\odot$  and  $3\theta_\odot$  respectively. From Liebig & Wambsganss (2010, Figures 2–3a,h), reproduced with permission © ESO.

deviations of the order of  $0.01\delta_p$ . They concluded that rings may be detectable with very large apertures ( $\geq 30$  m), whereas spots, satellites, and zonal bands will be difficult to detect. Atmospheric  $\text{CH}_4$ ,  $\text{H}_2\text{O}$ , and  $\text{Na/K}$  could be inferred from  $0.6\text{--}1.4\ \mu\text{m}$  spectroscopy (Spiegel et al., 2005), while polarisation would also probe atmospheric properties (Lewis & Ibata, 2000).

**Spots on the source star:** Detection of spots on the source star have been investigated as a function of surface brightness contrast, the size, the number, the umbra/penumbral structure, and the shape and orientation with respect to the sweeping caustic (Heyrovsky & Sasselov, 2000; Lewis, 2001; Chang & Han, 2002; Giordano et al., 2015; Sajadian, 2015).

**Planets transiting a lensed source:** In a combination of two low-probability phenomena, a planet transiting the source star during a caustic crossing event will result in significant and characteristic perturbations of the light curve (Lewis, 2001; Rybicki & Wyrzykowski, 2014). Predicted effects depend on the planet radius, the relative position of the planet in front of the star, and the orientation of the caustic crossing, and they may mimic the effects of star spots (Heyrovsky & Sasselov, 2000). The probability of observing such a configuration appears to be prohibitively small,  $\leq 5 \times 10^{-6}$  for an individual lensing event (Lewis, 2001; Rybicki & Wyrzykowski, 2014).

### 5.6.3 Physical effects

**Polarisation:** Polarisation measures may help resolve model degeneracies, with the polarisation angle (observable with large telescopes) and amplified polarisation signal giving additional information about the relative positions of the lens and source (Zakharov et al., 2014; Sajadian & Rahvar, 2015a; Sajadian, 2015; Sajadian & Rahvar, 2015b; Sajadian & Hundertmark, 2017).

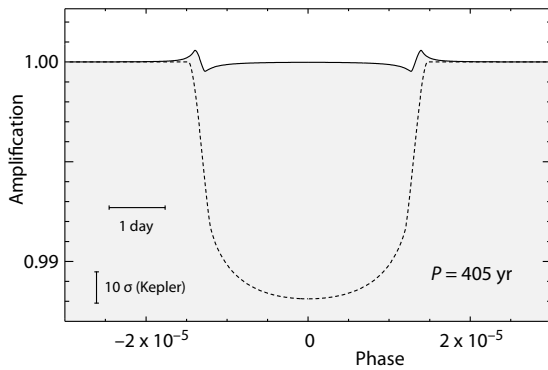


Figure 5.17: Transit light curve of a hypothetical  $0.05M_{\odot}$  brown dwarf in a wide orbit (55 au,  $P = 405$  yr) around a solar-type star. The solid curve includes both transit and lensing contributions (non-lensed transit is shown dashed). The slight positive amplification at ingress occurs because microlensing begins just before first contact (similarly at egress). From Sahu & Gilliland (2003, Figure 13), by permission of IOP Publishing/AAS.

**Light travel time:** For a lens producing two or more images of a single source, the light travel times along the distinct paths are different (Schneider, 1985). Two effects contribute: geometric time delay due to the different geometric path lengths, and relativistic (Shapiro) time delay due to gravitational time dilation (the divergence of coordinate time and proper time) in the gravity field. Although the time delay would be an important observable setting the scale of the system (image separations and brightness ratios being scale invariant), the effect (and measurement markers) are not yet within reach.

**Diffraction:** Microlensing in the optical is generally formulated in the limit of geometric optics. Expressions for *diffractive microlensing*, the magnification of a point source including the effects of diffraction, are given by Schneider et al. (1992) and Heyl (2011a). Diffraction modifies the lensing signature at longer wavelengths, specifically at wavelengths comparable to the Schwarzschild radius of the lensing object, and its effects may be detectable at radio wavelengths with the sensitivity and cadence of the Square Kilometer Array (SKA, §8.10.5).

Relevant for substellar objects but not for stars, such observations could place constraints on the lens mass and distance. For short time scale events (§5.10.2), one goal would be to distinguish between rapidly moving stellar mass lenses (e.g. neutron stars) and slowly moving substellar objects (such as free-floating planets). For massive Kuiper belt or Oort cloud objects, the effects of diffraction and microlensing may be detectable during an occultation (Heyl, 2010).

### 5.6.4 Transiting planets

**Near-field effects on transit light curves:** For typical planetary transits (Chapter 6), there is no discrete foreground lens, and the planet's gravitational lensing contribution is generally neglected: at orbit separations of a few au, the Einstein ring due even to a stellar-mass companion (acting as a lens) is typically much smaller than the size of the primary (the source), so that even the maximum amplification due to the lens is small.

When the gravitational deflection angle is comparable to the angular size of the occulting body, both lensing and occultation occur (§6.14.12). The former is important for degener-

ate companions, or possibly for substellar companions at large separation (Agol, 2002; Chang & Han, 2002; Sahu & Gilliland, 2003; Agol, 2003; Kasuya et al., 2011). Such events can be used to constrain the ratio of the lens and source sizes, limb-darkening effects of the star, and the surface gravity of the lens.

For brown dwarfs at separations of a few au, lensing could reach several percent of the transit depth, while for degenerate companions the effect could exceed the transit signal, even causing a net positive amplification. A distinctive feature of such a transit light curve would be a small positive amplification slightly before ingress, because lensing contributes just before first contact, and similarly at egress (Figure 5.17). The effect is seen in the M dwarf–white dwarf binary KOI-256, where the white dwarf Einstein radius ( $R_E/R_{\odot}=0.00473$ ) results in a transit depth smaller than expected from pure geometry (Muirhead et al., 2013).

**Radial velocity perturbations:** Radial velocity perturbations during transit (Rossiter–McLaughlin effect; §6.18.3) would also be affected by the planetary lensing (Oshagh et al., 2013b).

### 5.6.5 Specific targets

**Planets in M31:** Microlensing searches remain effective out to very large distances, and the situation where the source stars are unresolved is specifically referred to as *pixel lensing*. The possible detection of planets in M31 has been explicitly considered (Baltz & Gondolo, 2001; Chung et al., 2006; Ingresso et al., 2009; Calchi Novati et al., 2010). At least one event, PA-99-N2, showed small deviations from the single lens model (An et al., 2004; Ingresso et al., 2011).

**Application to SETI:** The microlensing magnification of SETI-type signals has been considered in the context of both radio detection (Rahvar, 2016b), and explicitly in the context of a space mission exploiting solar lensing (§5.7).

## 5.7 Solar system lensing

The expression for general relativistic light bending (Equation 5.1) also quantifies, for example, the displacement of star images due to the Sun's gravitational field as observed from Earth, i.e. at 1 au.

More generally, there exists a minimum focal length for the (opaque) Sun, given by the grazing-incidence condition  $b = R_{\odot}$ , approximated by

$$F_{\min} \equiv \frac{R_{\odot}}{\alpha_{\text{GR}}} = \frac{c^2 R_{\odot}^2}{4GM_{\odot}} \simeq 548.2 \text{ au}, \quad (5.43)$$

with  $F > F_{\min}$  for  $b > R_{\odot}$ , since  $\alpha_{\text{GR}} \propto b^{-1}$ . Hence the Sun's gravitational field acts as a spherical 'lens' which magnifies the radiation from a distant source along a semi-infinite focal line (Eshleman, 1979).<sup>3</sup> Other analogous planetary solar system foci exist (e.g. that of Jupiter at 6 kau), obviating effects of the solar corona.

<sup>3</sup>The dense core of the 'transparent' Sun has also been considered for enhanced detection of signals which pass through it, viz. gravitational waves (Lawrence, 1971; Clark, 1972; Ohanian, 1973) or neutrinos (Demkov & Puchkov, 2000; Escribano et al., 2001). Due to stellar power-law density profiles,  $F_{\min} \sim 25$  au, viz. between Uranus and Neptune (Patla & Nemiroff, 2008).

**FOCAL mission** The FOCAL mission was proposed to ESA in 1993 to exploit this sensitivity and angular resolution, with goals including exoplanet imaging and SETI detection (Heidmann & Maccone, 1994; Maccone & Matloff, 1994; Maccone, 1994a,b; Maccone & Piantà, 1997; Maccone, 2000, 2008, 2011a,b, 2013). To place a spacecraft at this location in a reasonable time, Maccone (1994b) considered an electrically-propelled inflatable antenna capable of reaching 550 au in 30 yr, comparable with the (parallax-driven) Thousand Astronomical Unit (TAU) technology study by JPL, which aimed to reach 1000 au in 50 yr (Etchegaray, 1987). Other practical difficulties include effects of the solar corona and solar light, the need for separate spacecraft for each stellar system, and assembling an exoplanet image from a raster scan around the focal line.

**Planet Nine** Amongst prospects for quantifying the nature of the hypothesised Planet Nine (at  $d \sim 700$  au; §12.5.8), Gaudi & Bloom (2005) suggested that it could be evidenced by the astrometric lensing by background stars, perhaps revealed over the entire sky by Gaia. Microlensing of a suitably aligned background star would induce potentially measurable magnification and astrometric displacement, of  $A \sim 4$  and  $\delta\theta \sim 0.1$  mas (Philippov & Chobanu, 2016; Schneider, 2017).

## 5.8 Astrometric microlensing

**Principles** In addition to the *photometric* manifestation of microlensing, time-varying magnification of the unresolved microlensed images also leads to a small time-varying displacement of their photocentre, typically by a fraction of a milliarcsec (Høg et al., 1995; Miyamoto & Yoshii, 1995; Walker, 1995; Paczyński, 1996; Miralda-Escudé, 1996; Sazhin, 1996; Boden et al., 1998; Honma & Kurayama, 2002).

The astrometric deflection of the centroid, from Equation 5.15, can be written

$$\delta\theta = \frac{A_+\theta_+ + A_-\theta_-}{A_+ + A_-} - \theta_S = \frac{u\theta_E}{u^2 + 2}, \quad (5.44)$$

where, again,  $u = \theta_S/\theta_E$ . This reaches a maximum deflection angle, at  $u = \sqrt{2}$ , of

$$\delta\theta_{\max} = 8^{-1/2}\theta_E \approx 0.35\theta_E. \quad (5.45)$$

For a typical bulge lens ( $\theta_E \sim 300 \mu\text{as}$ ),  $\delta\theta \sim 0.1$  mas.

Although the astrometric displacement is small, the astrometric cross section is substantially larger than the photometric, falling off as  $b^{-1}$  (Equation 5.1), meaning that the effect extends over larger angular scales. Furthermore, the normal degeneracy with respect to the mass of the lens is removed (Gaudi & Gould, 1997). This follows from Equation 5.40, where  $\varpi_{\text{rel}}$  is now the (measurable) relative parallax of the lens source assuming linear motion between the source and lens. Numerically

$$\frac{M_L}{M_\odot} = 0.123 \frac{\theta_E^2}{\varpi_{\text{rel}}}, \quad (5.46)$$

where  $\theta_E$  and  $\varpi_{\text{rel}}$  are in mas.

Higher-order effects may result from a finite lens and/or finite source size (Takahashi, 2003; Lee et al., 2010c), or from orbital motion of the lens (Sajadian, 2014).

**First measurement** Sahu et al. (2017) used HST to measure the astrometric microlensing displacement due to the nearby ( $d = 52$  pc) white dwarf Stein 2051B, although neither source nor lens are accompanied by planets. As the white dwarf (with  $R_E \sim 31$  mas) passed closely (in projection) in front of a background star, the background star position was deflected by  $\sim 2$  mas. Fits to the measured deflection at 8 epochs between 2013–15 yielded  $M_{\text{WD}} = 0.675 \pm 0.051 M_\odot$ , and a further confirmation of the physics of degenerate matter. This specific mesolensing-type configuration (see below) was one of the events predicted by Proft et al. (2011).

**Planet detection** Astrometric microlensing related to planet detection has been investigated theoretically, although not yet observed (Mao & Paczyński, 1991; Safizadeh et al., 1999; Han & Chang, 1999; Dominik & Sahu, 2000; Han & Lee, 2002; Han, 2002; Asada, 2002; Han & Chang, 2003; Zakharov, 2015; Nucita et al., 2017). Figure 5.18 shows predictions of Safizadeh et al. (1999). Although the planet's astrometric perturbation is short in duration, the amplitude can be large for Jovian planets, the duration for  $\delta\theta > 10 \mu\text{as}$  being of order days.

Such displacements are too small to be measured by present ground-based facilities. In the future, narrow-field astrometric interferometers, along the lines of (the discontinued) VLTI-PRIMA (Launhardt et al., 2008), and microarcsec space experiments, should be able to measure the effects. Concepts such as the (discontinued) NASA space interferometer SIM PlanetQuest (Unwin et al., 2008) would allow the astrometric study of photometric events alerted from ground (Paczynski, 1998).

While scanning missions offer less favourable observational conditions for planet detection, Gaia should detect astrometric lensing independently of photometric signatures (Dominik & Sahu, 2000). Belokurov & Evans (2002) estimated that there will be 1300 photometric microlensing events for which Gaia will measure at least one data point on the amplified light curve, with some 25 000 sources having a significant variation of the centroid shift, and some 2500 events for which the mass can be recovered with an error of better than 50%. The high-quality events are dominated by disk lenses within a few tens of pc, and source stars within a few hundred pc.

**Mesolensing** A distinct approach to identifying possible astrometric microlensing events is to select potential lenses rather than potential sources (Paczynski, 1995, 1998; Di Stefano, 2008a,b; Di Stefano et al., 2013).

Stars with high proper motion, which cross large areas of sky over a relatively short time, provide more opportunities for chance alignment, especially in the Galactic plane. High proper motion stars are also preferentially nearby, with a relatively large  $\theta_E$  and hence large astrometric cross section (Equation 5.45).

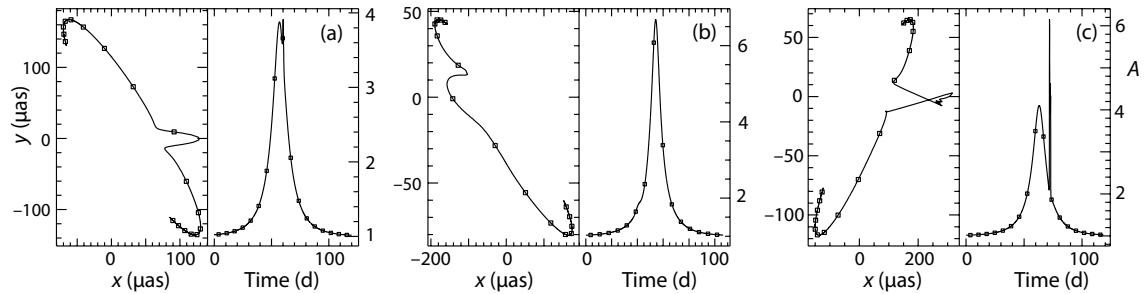


Figure 5.18: Predicted planet astrometric (leftmost plots of each pair, scale at left) and photometric (rightmost plots, scale at right) lensing curves. All assume a planet-to-lens mass ratio  $q = 10^{-3}$ , with a primary lens Einstein radius  $\theta_E = 550 \mu\text{as}$ , corresponding to  $M_P = M_{\text{Saturn}}$ . Data points are plotted one per week: (a)  $d = 1.3$ ; (b)  $d = 0.7$ ; (c) a caustic crossing event with  $d = 1.3$  ( $d$  is the projected planet–lens separation in units of  $\theta_E$ ). Both astrometry and photometry show a smooth perturbation due to the primary lens, with the short planetary event in addition. From Safizadeh et al. (1999, Figure 2), by permission of IOP Publishing/AAS.

Their proximity also improves prospects of independent detection, and thereby resolving the inherent degeneracy. This microlensing by a (nearby) high proper motion star has been referred to as *mesolensing* (Lépine & Di Stefano, 2012).

Hipparcos and Gaia stars with accurate high proper motions would allow suitable events to be predicted months or years in advance, and their astrometric displacements monitored. For Barnard’s star, for example, a background source at 9 arcsec separation would be displaced by  $100 \mu\text{as}$ . With a proper motion  $\mu \sim 10 \text{ arcsec yr}^{-1}$ , Barnard’s star would probe an area on the sky of  $\sim 30 \times 18 \text{ arcsec}^2$  over three years.

**Example cases** For the nearby low-mass star VB 10, Lépine & Di Stefano (2012) predicted a close approach to a background point source in late 2011, a 10% probability of a close approach  $\rho_{\text{min}} < 20 \text{ mas}$  (possibly observable with HST), resulting in a 6% magnification of the background source and an astrometric displacement of  $\delta\theta \sim 3.3 \text{ mas}$ . If VB 10 has a  $1M_J$  planet on a moderately wide (0.2–0.8 au) orbit, they estimated a 1–10% probability of a secondary event of higher magnification.

Sahu et al. (2014) predicted Proxima Cen passing close to a 20 mag star in 2014 October ( $\rho_{\text{min}} = 1.6 \text{ arcsec}$ ,  $\delta\theta \sim 0.5 \text{ mas}$ ), and a 19 mag in 2016 February ( $\rho_{\text{min}} = 0.5 \text{ arcsec}$ ,  $\delta\theta \sim 1.5 \text{ mas}$ ).

Proft et al. (2011) considered high-proper candidates for measurable astrometric microlensing during the Gaia operational phase (2012–2019). They identified nine candidates with expected centroid shifts between  $100\text{--}4000 \mu\text{as}$ , the strongest of which should be observable over several months.

## 5.9 Observations

Large-scale observing programmes, including those that detected the first microlensing planets, focus on Baade’s Window in the central Galactic bulge, visible from around April to September each year (the *bulge season*). High star densities (Figure 5.19) maximise the chances of detecting rare microlensing events; the inescapable disadvantages are the effects of crowding and blending on the photometric analysis of the background sources.

### 5.9.1 Ground-based: first generation (pre–2010)

**Two-step mode** Before the advent of observing techniques capable of observing tens of square degrees of sky several times per hour, early programmes focused on the detection of planetary microlensing events typically operated in a two-step mode (Gould & Loeb, 1992; Han & Kim, 2001; Han, 2007a). A wide-angle survey telescope was used to detect the early stages of a microlensing event using a relatively coarse time sampling. Once a deviation indicative of such an ongoing event was detected and issued as an alert, an array of smaller, follow-up narrow-angle telescopes distributed in Earth longitude followed the event with high-precision photometry and a much denser time coverage.

**Monitoring** Two monitoring teams, MOA and OGLE, each operating single dedicated telescopes, gathered detailed photometric information about lensing events sifted from the vast survey data streams, and generated alerts for several hundred ongoing microlensing events per year, based on difference-imaging photometry and real-time event detection (Bond et al., 2002a).

The problem of the early identification of developing high-magnification events is severe, given the typically faint sources with attendant poor photometric accuracy. Efforts to optimise this resulted in the OGLE Early Warning System (EWS) and the Early Early Warning System (EEWS) (Udalski et al., 2005), as well as anomaly feedback based on results from follow-up teams in the case of RoboNet–1.0 (Dominik et al., 2007b).

By 2007, MOA and OGLE were alerting a total of  $\sim 900$  events per year, ‘... ushering in the first golden age of microlensing planet searches’ (Gaudi, 2012).

**MOA** MOA (Microlensing Observations in Astrophysics, Bond et al. 2001, Abe et al. 2004) is a NZL/JPN collaboration. Phase I (2000–2005) employed a 0.6-m telescope on Mt John (NZL), with phase II, post-2006, using a 2-m telescope. Images were acquired in a broad  $I$ -centred band, using a  $4\text{k} \times 6\text{k}$  camera with exposures of 180 s. They covered some  $20 \text{ sq. deg.}$  a few times

**Early upper limits and uncertain detections:** Between 1997 and the first unambiguous microlensing planet in 2004, early results from the exoplanet microlensing surveys gave a number of unconfirmed or uncertain planet detections, and the first limits on the existence of planets based on the lack of detection of planetary signals.

Bennett et al. (1997), based on limited photometric coverage, suggested that MACHO-1994-BLG-4 could be an M-dwarf with a companion gas giant of  $5 M_J$  at 1 au, and that MACHO-1995-BLG-3 could be an isolated object of  $2 M_J$  or a planet more than 5–10 au from its parent star.

Bennett et al. (1999) claimed the first unambiguous detection of a Jupiter-mass planet orbiting a binary star MACHO-1997-BLG-41, but the independent PLANET data favoured a rotating binary with an orbital period of 1.5 yr (Albrow et al., 2000a; Jung et al., 2013).

Gaudi & Sackett (2000) analysed some 100 PLANET events, finding that more than 20 had sensitivity to perturbations that would be caused by a Jovian-mass companion to the primary. No unambiguous signatures were detected, indicating that Jupiter-mass planets at 1.5–3 au occur in less than one third of systems, with a similar limit applying to planets of  $3 M_J$  at 1–4 au.

Rhie et al. (2000) gave limits on Earth-mass planets from the high-magnification ( $A \sim 80$ ) event MACHO-1998-BLG-35. Albrow et al. (2000b) gave limits for a lower magnification event OGLE-1998-BLG-14. Albrow et al. (2001a) and Gaudi et al. (2002) analysed five years of null detections, suggesting that less than 33% of the lens stars in the inner Galactic disk and bulge could have companions of  $\geq 1 M_J$  between 1.5–4 au. Bond et al. (2002b) showed that the data for MACHO-1998-BLG-35 were consistent with the possible detection of a terrestrial planet.

Jaroszynski & Paczyński (2002) proposed that OGLE-2002-BLG-55 had a signal consistent with a planet, but Gaudi & Han (2004) noted other possible explanations. Tsapras et al. (2003) derived upper limits from three years of OGLE data (1998–2000). Snodgrass et al. (2004) derived upper limits from 389 OGLE observations from 2002. Yoo et al. (2004a) derived constraints from the high magnification event OGLE-2003-BLG-423.

per night, geared to high magnification events, detecting typically ten events per season with  $A_{\max} > 100$ .

**OGLE** OGLE (Optical Gravitational Lens Experiment, Udalski 2003) is a Polish/US collaboration operating a 1.3-m telescope on Las Campanas (CHL), and regularly monitoring some 200 million stars. It has developed from OGLE-I (the pilot phase, 1992–1995), OGLE-II (1996–2000), OGLE-III (also devoted to transiting planets, 2001–2009), and OGLE-IV (starting in 2009). During phase III, images were acquired in the  $I$  band, using an  $8k \times 8k$  camera with exposures of 120 s. OGLE-IV, focused on increasing the number of planet detections using microlensing, employs a 32-chip CCD camera.

**Follow-up** During the first generation two-step operational mode, three collaborations pursued possible planetary microlensing alerts: PLANET/RoboNet, MicroFUN, and MiNDSTeP. Both survey teams, OGLE and MOA, could also switch from survey to follow-up mode for confirmed high-magnification events.

As an example of the dense follow-up sampling,

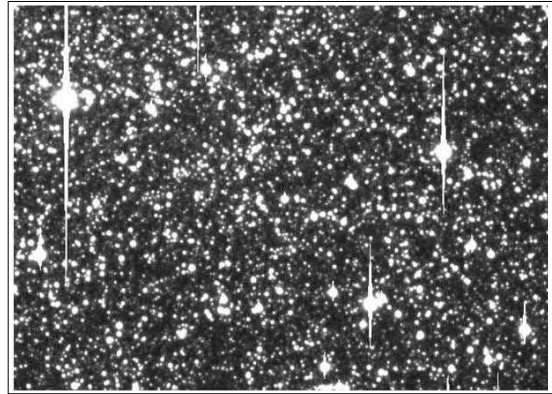


Figure 5.19: A small part of a MOA image of a field in the Galactic centre, obtained at Mt John University Observatory (NZL), showing a large density of faint stars. Image provided by the New Zealand–Japan MOA group, courtesy John Hearnshaw.

the PLANET team’s caustic crossing data of EROS-2000-BLG-5 (An et al., 2002) yielded a light curve of more than 1000 data points over several days with photometric accuracy of order 1%. Optimised follow-up schemes take account of telescope and other observing resources, and the predicted nature of the targets being observed (Horne et al., 2009, see also Figure 5.9).

**PLANET/RoboNET** Since 2005, PLANET/RoboNET (Beaulieu et al., 2007) has been a joint venture of the former PLANET collaboration (Probing Lensing Anomalies NETWORK, Albrow et al. 1998, Dominik et al. 2002, Sackett et al. 2004), with telescopes in Australia, S. Africa, and S. America, together with RoboNet-1.0 (Burgdorf et al., 2007), the UK-operated robotic network comprising the 2-m telescopes of Liverpool (La Palma, ESP), Faulkes-N (Maui, Hawaii), and Faulkes-S (Siding Spring, AUS). As of 2008, the two Faulkes telescopes are owned and operated by the Las Cumbres Observatory Global Telescope network, as part of their global deployment of robotic telescopes; plans exist for 18 new 1-m and 24 0.4-m telescopes (Hidas et al., 2008; Brown et al., 2013). RoboNet-II uses the same telescopes as RoboNet-1.0, but with improved software for prioritising and analysis (Tsapras et al., 2009; Hundertmark et al., 2018).

**MicroFUN** MicroFUN (Microlensing Follow-Up Network, Yoo et al. 2004b) is a consortium, coordinated by Ohio State University, which focuses on high-magnification events. The collaboration represents some 40 (professional and amateur) observers from 10 countries (including New Zealand, South Korea, Israel, and S. Africa), typically using 0.5-m telescopes.

**MiNDSTeP** MiNDSTeP (Microlensing Network for the Detection of Small Terrestrial Exoplanets, Dominik et al. 2010) is a large European/Eurasian effort also established to exploit the dense monitoring of lensing events.

**GMAN/MPS** A further monitoring group GMAN (Global Microlensing Alert Network, Pratt et al. 1996) subsequently placed its emphasis on non-planetary microlensing, while MPS (Microlensing Planet Search, Rhie et al. 1999) which began in 1997, merged with PLANET in 2004.



Table 5.1: Exoplanets discovered by microlensing, through to the end of 2017, ordered lexically by planet name – note that the announcement and discovery reference can be some years following the designated event. Lens distance  $D_L$ , host star mass  $M_\star$ , planet mass  $M_p$ , and projected star–planet separation  $a$ , number of planets in the system  $N_p$  are from the NASA Exoplanet Archive. They may be from the discovery paper or subsequent observations, and may be based on higher-order modeling or probability arguments. The planet/star mass ratio  $q = M_p/M_\star$  is derived from the tabulated masses.

Planet	$N_p$	$q$ ( $10^{-3}$ )	$D_L$ (kpc)	$M_\star$ ( $M_\odot$ )	$M_p$ ( $M_J$ )	$a$ (au)	Discovery reference
MOA-2007-BLG-192Lb	1	0.2	1.0	0.06	0.01	0.6	Bennett et al. (2008)
MOA-2007-BLG-400Lb	1	2.8	5.8	0.30	0.83	0.7	Dong et al. (2009a)
MOA-2008-BLG-310Lb	1	0.3	6.0	0.67	0.23	1.3	Janczak et al. (2010)
MOA-2008-BLG-379Lb	1	7.3	3.3	0.56	4.10	3.3	Suzuki et al. (2014)
MOA-2009-BLG-266Lb	1	0.1	3.0	0.56	0.03	3.2	Muraki et al. (2011)
MOA-2009-BLG-319Lb	1	0.4	6.1	0.38	0.16	2.4	Miyake et al. (2011)
MOA-2009-BLG-387Lb	1	13.5	5.7	0.19	2.56	1.8	Batista et al. (2011)
MOA-2010-BLG-073Lb	1	65.8	2.8	0.16	11.0	1.2	Street et al. (2013)
MOA-2010-BLG-117Lb	1	0.8	3.4	0.58	0.51	2.9	Bennett et al. (2018)
MOA-2010-BLG-328Lb	1	0.3	0.8	0.11	0.03	0.9	Furusawa et al. (2013)
MOA-2010-BLG-353Lb	1	1.5	6.4	0.18	0.27	1.7	Rattenbury et al. (2015)
MOA-2010-BLG-477Lb	1	2.2	2.3	0.67	1.50	2.0	Bachelet et al. (2012b)
MOA-2011-BLG-028Lb	1	0.1	7.4	0.75	0.09	4.1	Skowron et al. (2016)
MOA-2011-BLG-262Lb	1	0.5	7.0	0.12	0.06	0.8	Bennett et al. (2014)
MOA-2011-BLG-293Lb	1	5.6	7.7	0.86	4.80	1.1	Yee et al. (2012)
MOA-2011-BLG-322Lb	1	29.7	7.6	0.39	11.60	4.3	Shvartzvald et al. (2014)
MOA-2012-BLG-006Lb	1	16.3	5.3	0.49	8.4	10.2	Poleski et al. (2017)
MOA-2012-BLG-505Lb	1	0.2	7.2	0.10	0.02	0.9	Nagakane et al. (2017)
MOA-2013-BLG-605Lb	1	0.3	–	0.03	0.01	0.9	Sumi et al. (2016)
MOA-2016-BLG-227Lb	1	9.2	6.5	0.29	2.80	1.7	Koshimoto et al. (2017a)
MOA-bin-1Lb	1	4.9	5.1	0.75	3.70	8.3	Bennett et al. (2012)
OGLE-2003-BLG-235Lb	1	4.1	5.8	0.63	2.60	4.3	Bond et al. (2004)
OGLE-2005-BLG-071Lb	1	8.3	3.2	0.46	3.80	3.6	Udalski et al. (2005)
OGLE-2005-BLG-169Lb	1	0.1	4.1	0.69	0.04	3.5	Gould et al. (2006b)
OGLE-2005-BLG-390Lb	1	0.1	6.6	0.22	0.02	2.6	Beaulieu et al. (2006)
OGLE-2006-BLG-109Lb	2	1.4	1.5	0.51	0.73	2.3	Gaudi et al. (2008)
OGLE-2006-BLG-109Lc	2	0.5	1.5	0.51	0.27	4.5	"
OGLE-2007-BLG-349L AB c	1	0.6	2.8	0.41	0.25	2.6	Bennett et al. (2016)
OGLE-2007-BLG-368Lb	1	0.1	5.9	0.64	0.06	3.3	Sumi et al. (2010)
OGLE-2008-BLG-092L A b	1	0.3	8.1	0.71	0.18	18.0	Poleski et al. (2014a)
OGLE-2008-BLG-355Lb	1	12.4	6.8	0.37	4.60	1.7	Koshimoto et al. (2014)
OGLE-2011-BLG-251Lb	1	2.0	2.6	0.26	0.53	2.7	Kains et al. (2013)
OGLE-2011-BLG-265Lb	1	4.2	4.4	0.21	0.88	1.9	Skowron et al. (2015)
OGLE-2012-BLG-026Lb	2	0.1	4.0	1.06	0.15	4.0	Han et al. (2013b)
OGLE-2012-BLG-026Lc	2	0.8	4.0	1.06	0.86	4.8	"
OGLE-2012-BLG-358Lb	1	92.5	1.8	0.02	1.85	0.9	Han et al. (2013a)
OGLE-2012-BLG-406Lb	1	6.2	5.0	0.44	2.73	3.5	Poleski et al. (2014b)
OGLE-2012-BLG-563Lb	1	1.1	1.3	0.34	0.39	0.9	Fukui et al. (2015)
OGLE-2012-BLG-724Lb	1	1.6	6.7	0.29	0.47	1.6	Hirao et al. (2016)
OGLE-2012-BLG-950Lb	1	0.2	3.0	0.56	0.11	2.7	Koshimoto et al. (2017b)
OGLE-2013-BLG-102Lb	1	125.7	3.0	0.10	12.57	0.8	Jung et al. (2015)
OGLE-2013-BLG-132Lb	1	0.5	3.9	0.54	0.29	3.6	Mróz et al. (2017b)
OGLE-2013-BLG-341L B b	1	0.1	1.2	0.15	0.01	0.9	Gould et al. (2014)
OGLE-2013-BLG-1721Lb	1	1.3	6.3	0.46	0.64	2.6	Mróz et al. (2017b)
OGLE-2014-BLG-124Lb	1	0.7	4.1	0.71	0.51	3.1	Udalski et al. (2015b)
OGLE-2014-BLG-676Lb	1	5.0	2.2	0.62	3.09	4.4	Rattenbury et al. (2017)
OGLE-2014-BLG-1760Lb	1	1.1	6.9	0.51	0.56	1.8	Bhattacharya et al. (2016)
OGLE-2015-BLG-051Lb	1	7.2	8.2	0.10	0.72	0.7	Han et al. (2016b)
OGLE-2015-BLG-954Lb	1	11.8	0.6	0.33	3.90	1.2	Shin et al. (2016)
OGLE-2015-BLG-966Lb	1	0.2	2.5	0.38	0.07	2.1	Street et al. (2016)
OGLE-2016-BLG-263Lb	1	30.1	6.5	0.13	4.10	5.4	Han et al. (2017c)
OGLE-2016-BLG-613L AB b	1	5.7	3.4	0.72	4.18	3.0	Han et al. (2017d)
OGLE-2016-BLG-1190Lb	1	14.4	6.8	0.89	13.38	2.1	Ryu et al. (2018)
OGLE-2016-BLG-1195Lb	1	0.1	3.9	0.08	0.01	1.2	Bond et al. (2017b)

### 5.9.2 Ground-based: second generation (post-2010)

The second generation microlensing network aims to circumvent the two-step approach to event detection (surveys for alerts, and follow-up search mode). Instead,

wide-field cameras on 2-m class telescopes around the Earth aim to monitor several square degrees of the Galactic bulge, with cadences high enough to detect planetary anomalies without follow-up observations or

switching to higher cadence. It aims for a 10–100-fold increase in the events probed ( $\sim 6000$  per year) and, correspondingly, in the number of planet detections, embracing low-mass planets ( $\sim 1M_{\oplus}$ ), as well as short time scale events due to free-floating or wide-separation planets (Gould et al., 2007; Han, 2007b, 2009; Gaudi, 2012; Shvartzvald et al., 2014; Chung et al., 2014).

**MOA, OGLE, Wise, and KMTNet** Since 2011, three groups have continuously monitored 8 sq. deg. of the Galactic bulge, with cadences of 15–30 min throughout the bulge season: (a) the MOA collaboration upgraded to the dedicated MOA-II telescope in New Zealand, with a diameter of 1.8 m and a 2.2 sq. deg. field (Sako et al., 2008); (b) the OGLE collaboration began the OGLE-IV phase in 2010, with an upgraded 1.4 sq. deg. camera on their dedicated 1.3-m telescope at Las Campanas in Chile (Udalski, 2009); (c) the Wise Observatory 1.0-m telescope (Israel) was equipped with a 1 sq. deg. camera (Gorbikov et al., 2010). Together, Shvartzvald & Maoz (2012) estimated a planet detection efficiency of  $\sim 20\%$ .

In the 2011 season, there were 80 events in the survey region common to MOA, OGLE, and Wise, with 218 other events observed by only two groups. Of those 80 events, at least three showed a clear planetary anomaly: MOA-2011-BLG-293 (Yee et al., 2012), MOA-2011-BLG-322 (Shvartzvald et al., 2014) and OGLE-2011-BLG-265 (Skowron et al., 2015). Accounting for the detection efficiency, these results imply a fraction of planetary systems of 0.2, consistent with previous estimates by Gould et al. (2010b).

The first lensing planet from the second generation observations, MOA-2011-BLG-293 (Yee et al., 2012), was based on the new survey mode data including follow-up observations, while MOA-2011-BLG-322 (Shvartzvald et al., 2014) was the first lensing planet discovery based on the survey data alone.

Since 2015, these have been supplemented by the Korean Microlensing Telescope Network, KMTNet.

**KMTNet** The Korean Microlensing Telescope Network (KMTNet: Lee et al., 2014b, 2015b; Kim et al., 2016), funded by the Korean government, comprises three identical 1.6-m telescopes in the southern hemisphere with  $2 \times 2$  sq. deg. cameras, in S. Africa (SAAO, Sutherland), S. America (CTIO, Cerro Tololo), and Australia (SSO, Siding Springs). It provides larger apertures and fields for most longitudes, more continuous access to the Galactic bulge (with S. Africa), and some (weather) redundancy with telescopes in Australia (cf. New Zealand for MOA) and S. America (cf. Las Campanas for OGLE). The 10 min sampling still benefits from follow-up observations to extract the full scientific potential of very high magnification events.

Henderson et al. (2014) estimate annual yields of 2200 microlensing events, 20 planets per dex in mass across the range  $5 - 1000M_{\oplus}$  with  $a \sim 0.4 - 16$  au, 10 in the range  $0.1 - 5M_{\oplus}$ , and  $\sim 1$  free-floating planet. Simulations based on the Ida et al. (2013) core accretion model for  $0.3M_{\odot}$  stars are given by Zhu et al. (2014c). Follow-up prospects for object characterisation are described by Henderson (2015).

**Naming convention:** Microlensing events are designated as TEAM-YEAR-BLG-NNN, characterising the discovery team and event epoch, with BLG designating the Galactic bulge, and NNN a sequential candidate identifier. They are named after the team who first reported them, so that while OGLE-2003-BLG-235 and MOA-2003-BLG-53 refer to the same event, the former takes precedence.

The lens and source can be specified with the suffixes 'L' and 'S' respectively. Additional capital or lower case letters designate companions of stellar or planetary mass respectively. Accordingly OGLE-2006-BLG-109LA, OGLE-2006-BLG-109Lb, and OGLE-2006-BLG-109Lc designate specifically the star, and the two known planets of this multiple lens system. Similarly ...Sb would refer to a planetary companion to the source star (a configuration that has not been observed to date, cf. §5.6).

KMTNet also designate their confirmed discoveries sequentially, with their first (unconfirmed) discovery KMT-2015-1 b ( $\equiv$  KMT-2015-BLG-48; Hwang et al., 2015).

Observations started in 2015 February. The first discovery (unconfirmed) was KMT-2015-1 b (KMT-2015-BLG-48), a  $2M_J$  planet orbiting an M-dwarf (Hwang et al., 2015).

### 5.9.3 Ground-based: other

**UKIRT** During the 2015 and 2016 bulge observing seasons, the first near-infrared microlensing surveys were carried out with the UK Infrared Telescope (UKIRT), in conjunction with the Spitzer and Kepler microlensing campaigns, and a number of candidates have been reported (Shvartzvald et al., 2017a). Observations probe the (high event rate) regions of the Galactic plane and Galactic centre inaccessible to optical surveys due to high extinction. Their wavelength overlaps that of the planned WFIRST microlensing survey, and will provide improved event rates for WFIRST.

**First event** After the nominal cut-off date for this review, the first UKIRT microlensing event, UKIRT-2017-BLG-001L b, was reported by Shvartzvald et al. (2018). With high extinction ( $A_K = 1.68$ ) and  $0^{\circ}35$  from the Galactic centre, the  $1.5M_J$  planet, at  $d = 6.6$  kpc, is likely to lie in the Galactic bulge.

**Observations from the Antarctic** The rationale for a 2-m class Antarctic telescope, providing more continuous target monitoring under improved atmospheric conditions, especially important for the smallest planets, has been discussed in the framework of astronomy from the Antarctic (Yock, 2006; Lawrence et al., 2009).

**Improved angular resolution** The proposed Gravity-Cam microlensing survey at the ESO NTT targets improved angular resolution over a wide field of view (Mackay et al., 2017). It is achieved through atmospheric tip-tilt distortion correction (the first step in 'lucky imaging', which also compensates for atmospheric defocus; §7.3.2), and implemented using an array of low-noise high-speed readout CCDs. Results would be improved further with the use of CMOS detectors, both in terms of sky area monitored and improved photometry.

**Large Synoptic Survey Telescope** With full observations expected to start in 2023 (§6.4.4), an LSST survey of the Galactic plane, with deep images every 3–4 d, could identify some 250 planetary microlensing events in the Galactic disk, including some 10% of high-magnification,  $A > 100$  (Gould, 2013b; Yee et al., 2018).

#### 5.9.4 Space-based: ongoing

In addition to a number of follow-up observations of individual events with HST and Spitzer, more dedicated/coordinated microlensing campaigns were carried out in 2015 with Spitzer, and in 2016 as part of the K2 extension to the Kepler mission (see §6.6.3).

For Spitzer, a pilot programme in 2014 aimed to demonstrate the ability to measure microlens parallax (e.g. Calchi Novati et al., 2015; Udalski et al., 2015b; Yee et al., 2015b; Zhu et al., 2015b), with individual results described above. A wider campaign started in 2015, in coordination with detections from the ground, with the goal of determining the Galactic distribution of planets (Calchi Novati et al., 2015; Yee et al., 2015a). The 2015 campaign observed 170 such microlensing events detected with OGLE, MOA, and KMTNet. First statistical results are described by Zhu et al. (2017b).

#### 5.9.5 Space-based: future

Surveys from space would circumvent two key problems faced by ground-based observations. The first is the crowding of source stars in the Galactic bulge, for which blending would be strongly reduced in the absence of atmospheric seeing, although not entirely suppressed (Han, 2005b). Space observations would also give uninterrupted photometric time coverage over hours or days (Peale, 2003). Access to broader infrared coverage would also be advantageous, especially in the high-extinction regions of the Galactic centre.

Earlier proposed dedicated concepts, GEST and MPF, have been superseded by two missions primarily focused on constraining dark energy, but with a significant fraction of time to be made available for microlensing surveys: Euclid and WFIRST.

**GEST/MPF** Microlensing Planet Finder (MPF) was a proposed Discovery-class mission (Bennett & Rhie, 2002; Bennett et al., 2004), succeeding the earlier Galactic Exoplanet Survey Telescope concept (GEST, Bennett et al., 2003). With a mirror diameter 1.1 m, pointing stability 24 mas, spectral range 600–1600 nm in two bands, and duration 3.7 yr, it was to continuously view two 1.3 sq. deg. fields in the Galactic bulge.

**Euclid** Euclid is an approved and funded ESA mission, with launch scheduled for 2020. A 1.2-m aperture telescope will image distant galaxies to detect the effects of dark energy. As a secondary goal, Euclid will conduct a 3–12 month microlensing programme predicted to detect some 1000 ‘cold’ exoplanets per month (from  $a \gtrsim 1$  au out to the free-floating or unbound regime) over 1.6 sq. deg. of the Galactic bulge (Beaulieu et al., 2010a; Penny et al., 2013; Hamolli et al., 2013).

Euclid will also detect transits, with observations in both optical (VIS) and H-band (NISIP-H, Near Infrared Spectrometer and Photometer). Despite Euclid’s target star field being crowded and the targets faint, complicating transit detection compared with Kepler, predictions indicate some 4000 transiting substellar objects, ~600 detectable in both VIS and NISIP-H, of which ~500 are hot Jupiters, and with secondary eclipses detectable in ~100 systems (McDonald et al., 2014).

**WFIRST** The 2010 US Decadal Survey (Blandford et al., 2010) proposed, as its highest priority for new large space activities, a Wide Field Infrared Survey Telescope (WFIRST). The original design, studied in 2011–2012, featured a 1.3-m primary mirror, and comprised a single instrument, a visible to near-infrared imager and slitless prism spectrometer. In 2012, the design evolved to include an available National Reconnaissance Office 2.4-m telescope, since referred to as WFIRST-AFTA (Astrophysics Focused Telescope Assets, Spergel et al., 2013b,a). It was formally designated as a NASA mission in 2016 February, with launch in the mid-2020s.

The mission now combines two distinct scientific objectives: a dark energy probe targeting cosmic shear measurements based on JDEM–Omega (Gehrels, 2010), and a microlens exoplanet survey based on MPF (including a coronagraph for direct imaging). The latter may consist of six 72-day continuous campaigns with 15-min cadence covering  $10^8$  stars in 2.8 deg<sup>2</sup> of the Galactic bulge, and is expected to detect thousands of events down to Mars-mass planets with  $a \gtrsim 1$  au (Yee, 2013; Yee et al., 2014; Zhu & Gould, 2016; Barclay et al., 2017).

## 5.10 Results

### 5.10.1 Individual objects

Since the first microlensing planet discovery in 2003, 53 planets have been announced by the end of 2017, or about three per ‘bulge season’ (Table 5.1). Others await analysis and publication. The rate has increased systematically over this time (with the upgrades to MOA–II in 2006, to OGLE–IV in 2009, and with the Wise Observatory in 2011), with a continuing development expected with the second-generation observations (§5.9.2).

Systems span a wide range of host star mass (0.02 –  $1.1 M_{\odot}$ ), and planet mass (from  $2 M_{\oplus}$ , OGLE–2013–BLG–341LB, to  $12 M_J$ , OGLE–2013–BLG–102L). Two of the (single star) systems contain two planets (OGLE–2006–BLG–109L and OGLE–2012–BLG–26L). One detection is a possible moon (MOA–2011–BLG–262).

There are single planets in four stellar binary systems, two circumprimary (OGLE–2008–BLG–92 and OGLE–2013–BLG–341) and two circumbinary (OGLE–2007–BLG–349 and OGLE–2016–BLG–613).

Summaries of some of the systems of particular interest are given in the accompanying box (page 145), with bibliography of all systems in Appendix E. Example light curves are shown in Figures 5.20–5.28.

Other microlensing results of interest for understanding planet formation mechanisms and microlensing analyses, but not falling within the accepted definition of planets, include various low-mass stellar

binaries such as OGLE-2005-BLG-153 (Hwang et al., 2010), OGLE-2009-BLG-92 (Ryu et al., 2010), and OGLE-2009-BLG-23 (Hwang et al., 2011); brown dwarf companions (e.g. Shin et al., 2012; Choi et al., 2013b; Han et al., 2017b); the M dwarf–brown dwarf binary MOA-2009-BLG-411 (Bachelet et al., 2012a); and a handful of brown dwarf–brown dwarf binaries including OGLE-2016-BLG-1469 (Han et al., 2017e).

### 5.10.2 Statistical results

Tsapras et al. (2016) used six years (2003–2008) of OGLE-III observations (with 2433 light curves satisfying their quality criteria) to derive the survey detection efficiency for a range of planetary masses and projected distances from the host star. They employed a Galactic model to convert from dimensionless to physical units ( $a/a_u$ ,  $M_\oplus$ ), finding the highest survey sensitivity to small planets at 1–4 au, shifting to slightly larger separations for more massive ones.

**Event rates and time scales** Clanton & Gaudi (2014a) compared the (median) event properties of the unbiased sample of 13 high-magnification events of Gould et al. (2010b) with simulated values derived from a Galaxy model (including contributions from both disk and bulge events). The observed median values are

$$\begin{aligned} R_{E,\text{med}} &= 2.36 \text{ au} \\ t_{E,\text{med}} &= 30.5 \text{ d} \\ D_{L,\text{med}} &= 3.35 \text{ kpc} \\ M_{L,\text{med}} &= 0.470 M_\odot \\ |\mu|_{\text{med}} &= 4.70 \text{ mas yr}^{-1}, \end{aligned} \quad (5.47)$$

compared with the simulated values

$$\begin{aligned} R_{E,\text{med}}^s &= 2.52 \text{ au} \\ t_{E,\text{med}}^s &= 27.9 \text{ d} \\ D_{L,\text{med}}^s &= 6.74 \text{ kpc} \\ M_{L,\text{med}}^s &= 0.434 M_\odot \\ |\mu|_{\text{med}}^s &= 5.12 \text{ mas yr}^{-1}. \end{aligned} \quad (5.48)$$

The discrepancy in  $D_L$  would be reduced if giant planets do not occur around bulge stars.

Sumi et al. (2011) found that the observed distribution of event time scales from the MOA survey, peaking at  $\sim 30$  d, drops off rapidly below  $\sim 10$  d and above  $\sim 100$  d (Sumi et al., 2011). The Gould et al. (2010b) sample of 13 high-magnification events are somewhat biased towards longer time scale events.

**Beyond the snow line** Discussions of microlensing results emphasise its contribution to detecting planets beyond the *snow line*, the region of the protoplanetary disk

where the mid-plane temperature falls below the sublimation temperature of  $\text{H}_2\text{O}$  (box, page 565).

Assuming that the snow line in the solar system is close to  $a_{\text{sl},M_\odot} \sim 2.7$  au (Abe et al., 2000; Rivkin et al., 2002), that this scales linearly with host star mass,  $a_{\text{sl}} \propto (M_L/M_\odot)$  (Kennedy & Kenyon, 2008b), accounting for a median projection factor  $a_{\text{sl},\perp} = 0.866 a_{\text{sl}}$ , and evaluating the linear Einstein radius (Equation 5.11) for a representative  $D_L \sim D_{LS} \sim 0.5 D_S$ , with  $D_S \sim 8$  kpc, indicates a peak sensitivity at  $R_E \sim 4$  au compared to a projected snow line at 2.3 au for  $M_L \sim 1 M_\odot$ , and at  $R_E \sim 2.9$  au compared to a projected snow line at 1.2 au for  $M_L \sim 0.5 M_\odot$ . Consequently, in the range  $0.5 - 1 M_\odot$ , the peak microlensing sensitivity is at roughly twice the snow line.

The discovery space as a function of (projected) semi-major axis in units of the snow line is shown in Figure 5.29, illustrating the contribution of microlensing to the discovery of wide separation planets.

Results suggest that super-Earths or Neptunes are more common than gas giants beyond the snow line (Sumi et al., 2010; Cassan et al., 2012; Shvartzvald et al., 2016; Suzuki et al., 2016), broadly in line with core accretion theory, which predicts that ‘failed Jupiters’, with  $M_p \sim 10 M_\oplus$ , should be quite common.

**Occurrence in the Galactic bulge** Penny et al. (2016) compared a sample of 31 microlensing planet discoveries with the expected distribution of distances and relative proper motions from a simulated microlensing in which the relative abundance of planets in the bulge to that in the disk,  $f_{\text{bulge}}$ , is a model parameter. They found consistency only for  $f_{\text{bulge}} \lesssim 0.54$ , hinting that the bulge may be underpopulated by planets relative to the disk.

**Occurrence around M dwarfs** Core accretion theory suggests that it is difficult for gas giants to form around M-dwarfs, with ‘failed Jupiters’ expected to be much more common than gas giants (Laughlin et al., 2004a); although Boss (2006c) has argued that the gravitational instability model could also create such planets.

While radial velocity observations confirm this picture (Johnson et al., 2007a, 2010a; Bonfils et al., 2013a), microlensing results were initially reported as discrepant (Gould et al., 2010b; Cassan et al., 2012): with host stars dominated by M dwarfs, nearly 20% have gas giants with  $M_p > 0.3 M_J$  (Cassan et al., 2012). However, planets found by microlensing typically orbit beyond the snow line, and are often of relatively low mass,  $\sim 0.3 M_J$  (Gould et al., 2010b), and so are less readily detected in radial velocity surveys.

Statistical occurrence constraints around M dwarfs can be derived from the different ranges of orbital period and planet mass probed by radial velocity and microlensing surveys (Clanton & Gaudi, 2014a,b). Clanton & Gaudi (2014a) suggested that the original discrepancy could originate from the steep slope of the planet mass

**Individual microlensing discoveries:** This listing of noteworthy discoveries is ordered by discovery announcement, reflecting the chronology of advances in instrumentation and analysis. A full listing of microlensing planet discoveries, ordered lexically by planet name, is given in Table 5.1 (with the main system parameters) and Appendix E (giving a more complete bibliography).

**OGLE-2003-BLG-235 (MOA-2003-BLG-53)** Bond et al. (2004) reported the first confirmed microlensing planet (Figure 5.20).

The long-term light curve is typical for a point mass event, while the two sharp spikes correspond to the caustic entry and exit, their short duration indicating an extreme mass-ratio binary system ( $q = 0.0039$ ). The probable detection of the host star using multicolour HST observations (Bennett et al., 2006) provides an estimate of the lens star spectral type (a K-dwarf), and of its distance and linear transverse motion, and thereafter a complete solution of the lens system.

**OGLE-2005-BLG-71** Udalski et al. (2005) reported the second microlensing planet (Figure 5.21). HST observations suggest an M dwarf at  $D_L = 3.2$  kpc,  $M_p = 3.8M_J$ ,  $a = 3.6$  au, and an equilibrium temperature  $T_{eq} \sim 55$  K (Dong et al., 2009b).

**OGLE-2005-BLG-169** Gould et al. (2006b) reported a Neptune-mass companion to the lens star in the extremely high magnification event,  $A \sim 800$ . It was flagged on 2005 April 21 as a faint ( $I = 19.4$  mag) but brightening bulge source, reaching  $I \sim 13$  mag at maximum. Following their predictions, Bennett et al. (2015) used HST to confirm their estimated lens-source relative proper motion of  $7\text{--}10$  mas yr $^{-1}$ , to determine the host star flux, and to refine the star/planet parameters.

**OGLE-2006-BLG-109** Gaudi et al. (2008) reported the first multi-planet microlensing system (Figure 5.22). Although the caustics of the two planets merge to form a single caustic curve, parts of the caustic associated with the individual planets could be identified. Using the finite source size during caustic exit provided the source radius,  $\rho = \theta_\star / \theta_E$ , and hence  $\theta_E$  based on an estimated  $\theta_\star$  from the source spectral type. Other distortions in the light curve were attributed to acceleration of the Earth's orbit (and the first measurement of a planetary system microlens parallax,  $\omega$ ), leading to an estimate of the physical size of the Einstein radius projected onto the plane of the observer  $R'_E$  (§5.5.5). These two measures of the Einstein radius allowed event triangulation, and hence the host star distance,  $D_L = 1.49$  kpc and  $M_\star = 0.50M_\odot$ . Orbital motion of the outer planet (planet c) could also be discerned from the changing projection geometry of the planetary caustic, leading to both a rotation and change of shape of the caustic during the event. They could then constrain the two components of the planet's projected velocity relative to the primary star which, together with  $M_\star$ , completely determine the outer planet's orbit (including inclination) on the assumption that it is circular. Orbital parameters of planet b followed from assumptions of circularity and co-planarity. Resulting planet masses are  $0.71$  and  $0.27M_J$ , at (true) orbital separations  $2.3$  and  $4.6$  au.

**MOA-2009-BLG-387** Batista et al. (2011) reported a high planet-to-star mass ratio with pronounced deviations over 12 d (Figure 5.23). The host is an M dwarf, with a mass estimated from the measured  $\theta_E = 0.31 \pm 0.03$  mas, and the microlens parallax due to the Earth's orbital motion, which is itself degenerate with the planet orbital motion. They resolved the degeneracy between the Earth and planet orbital effects statistically by imposing priors from a Galactic model.

**MOA-2009-BLG-319** Miyake et al. (2011) discovered this event from the high-cadence MOA-II survey monitoring, allowing identification as a high magnification event 24 h prior to its peak, and subsequent observation by 20 different telescopes.

**MOA-2009-BLG-266** Muraki et al. (2011) reported the detection of this  $10.4M_\oplus$  planet with  $P = 7.6$  yr (Figure 5.24). They determined the system masses through the microlens parallax light curve distortion due to the orbital motion of the Earth as well as with the (heliocentric orbit) EPOXI (Deep Impact) spacecraft.

**MOA-2010-BLG-477** Bachelet et al. (2012b) reported this high-magnification event planet (Figure 5.25). Their estimate of the host star mass,  $0.13 - 1.0M_\odot$ , is further restricted to  $0.67M_\odot$  by including Bayesian priors.

**MOA-2011-BLG-293** Yee et al. (2012) reported the first lensing planet based on the second-generation survey data.

**OGLE-2012-BLG-26** Han et al. (2013b) reported the second multiple-planet system discovered by microlensing in this high-magnification event (Figure 5.26). The complex central perturbation with multiple features was modeled by two planets located near the Einstein ring of the planet host star. The individual planets are beyond the snow line in all solutions.

**MOA-2010-BLG-73** Street et al. (2013) identified the source of this lensing event as a red giant (from its estimated radius). The microlens parallax was determined from the long event crossing time,  $t_E = 44.3$  d, while the source trajectory relative to the large caustic structure allowed detection of the orbital motion of the lens system.

**MOA-2011-BLG-262** Bennett et al. (2014) considered this the first candidate for a free-floating exoplanet-exomoon system, with a primary lens mass of  $4M_J$  hosting a sub-Earth mass moon (Fig. 5.27), based on the best-fit solution having a large lens-source relative proper motion (an alternate star-planet interpretation is also possible).

**OGLE-2008-BLG-92** Poleski et al. (2014a) identified a  $4M_{\text{Jupiter}}$  planet orbiting a  $0.7M_\odot$  star at  $a \sim 18$  au. The host star is binary, with a stellar or brown dwarf companion at a projected separation three times larger than the planet (Figure 5.28).

**OGLE-2014-BLG-124** Udalski et al. (2015b) combined Spitzer with ground-based observations to determine the first space-based parallax,  $\omega_E$ , and thus the mass and distance of the lens ( $M_p \sim 0.5M_J$ ,  $M_L \sim 0.7M_\odot$ , projected  $a \sim 3.1$  au).

**MOA-2013-BLG-605** Sumi et al. (2016) reported the first Neptune-analogue planet in a Neptune-like orbit.

**OGLE-2015-BLG-954** Shin et al. (2016) used KMTNet to identify an event with a source crossing time of only 16 min.

**OGLE-2012-BLG-950** Koshimoto et al. (2017b) reported masses determined only on the microlens parallax and the lens flux.

**OGLE-2007-BLG-349(AB)** Bennett et al. (2016) reported the first circumbinary lensing event.

**OGLE-2015-BLG-263** Han et al. (2017c) discovered this as a 'repeating event', in which the companion produced its own single-mass light curve after the event produced by the primary had ended.

**MOA-2010-BLG-117** Bennett et al. (2018) identified this as the first star-planet lens ( $M_p = 0.5M_J$ ,  $M_\star = 0.6M_\odot$ ) associated with a binary star source at  $D_S = 6.8 \pm 0.6$  kpc.

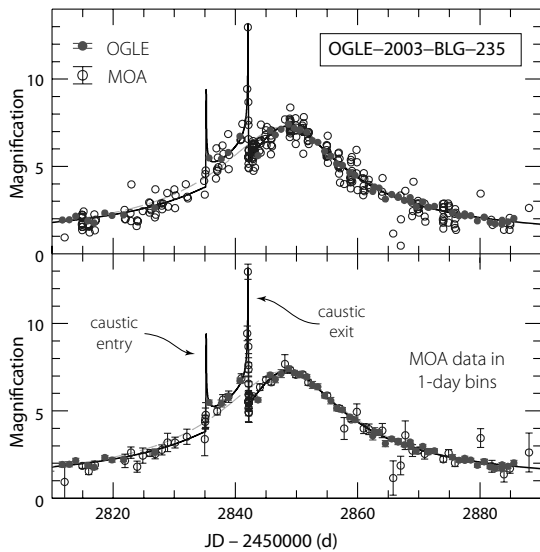


Figure 5.20: The first microlens planet, OGLE-2003-BLG-235, over a period of about 80 d during 2003. The bottom panel shows binned data. Caustic crossings (entry and exit) occur on days 2835 and 2842. The binary and single lens fits are shown by the solid and fainter (lower) lines respectively. From Bond et al. (2004, Figure 1), by permission of IOP Publishing/AAS.

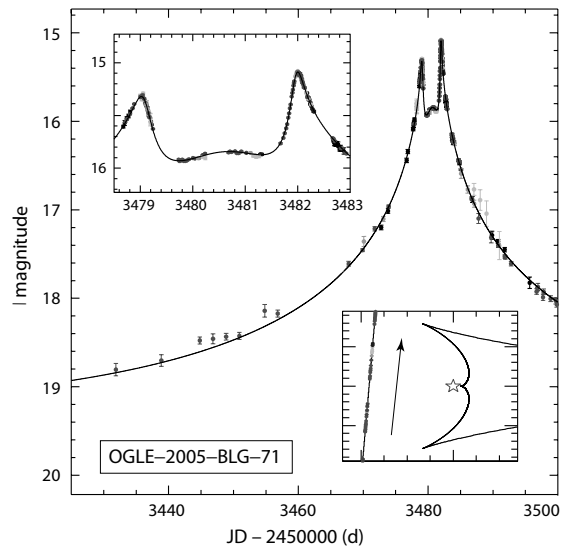


Figure 5.21: The second microlens planet, OGLE-2005-BLG-71. The upper inset shows an enlargement of the planetary anomaly near peak magnification. The triple peak indicates that the source passed three cusps of a caustic (lower inset), the middle one being relatively weak. From Udalski et al. (2005, Figure 1), by permission of IOP Publishing/AAS.

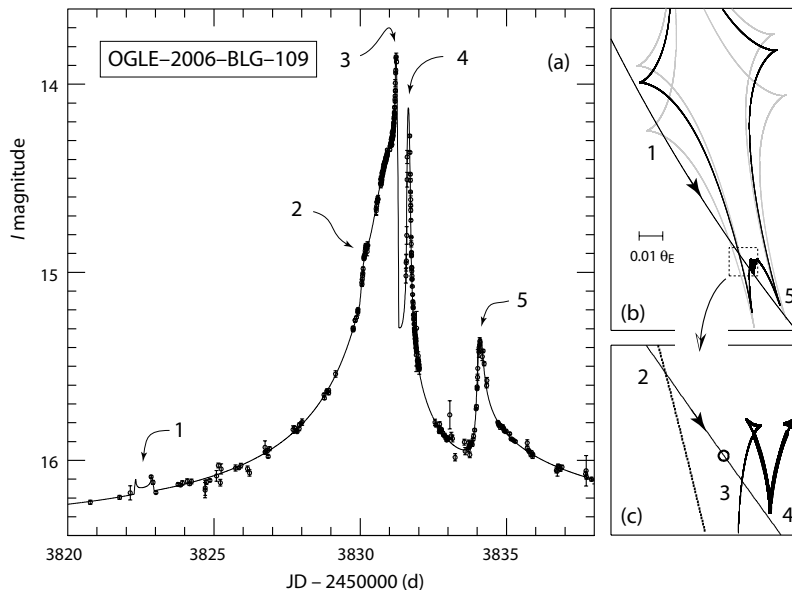


Figure 5.22: The two planet system OGLE-2006-BLG-109: (a) the light curve, with all data points from OGLE, MicroFUN, MOA, PLANET, and RoboNet; (b) and inset (c): the reconstructed path of the source, whose size is indicated by the circle in (c), is shown by the arrowed lines. The heavier line shows the position of the combined two-planet caustic at the peak of the event (feature 3); the lighter diamond-shaped curves show the combined caustic at two other epochs corresponding to features 1 and 5 (the three span about 10 d). The five numbered features are caused by the source approaching or crossing the combined caustic, whose shape and orientation change mainly because of the orbital motion of the outer planet. The majority of the caustic is due to the outer planet. The additional cusp (the thick line in c) corresponds to feature 4, and is due to the inner planet. The horizontal bar in (b) shows the angular scale of  $0.01 \theta_E \sim 15 \mu\text{as}$ . From Gaudi et al. (2008, Figure 1), reprinted with permission from AAAS.

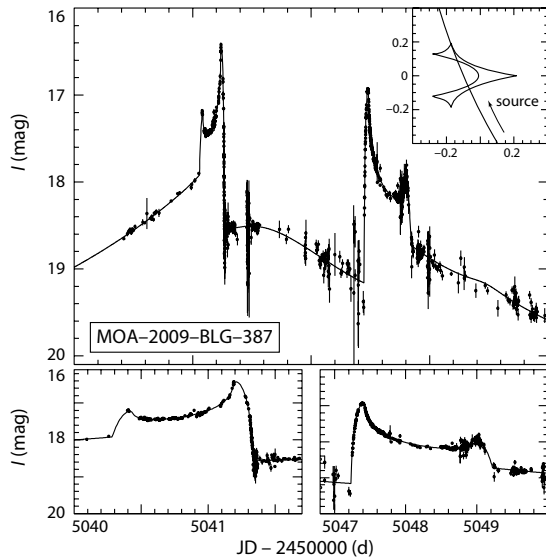


Figure 5.23: Light curve of the microlensing event MOA-2009-BLG-387 near its peak in July 2009, with the trajectory of the source across the caustic feature shown in the inset. The model includes the effects of finite-source, parallax and orbital motion. Bottom: details of the two caustic features. In the original figure, data from different observatories are distinguished by colour. From Batista et al. (2011, Figure 1), reproduced with permission © ESO.

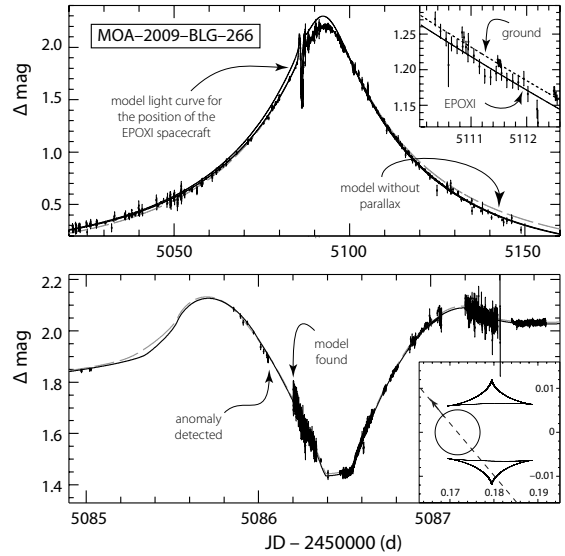


Figure 5.24: Light curve of the microlensing event MOA-2009-BLG-266. The lower panel shows details of the planetary deviation. The grey-dashed curves show the best fit non-parallax microlensing model. The inset shows the planetary caustic, the circle indicating the size of the source star. In the original figure, data from different observatories are distinguished by colour. From Muraki et al. (2011, Figures 1 and 5), by permission of IOP Publishing/AAS.

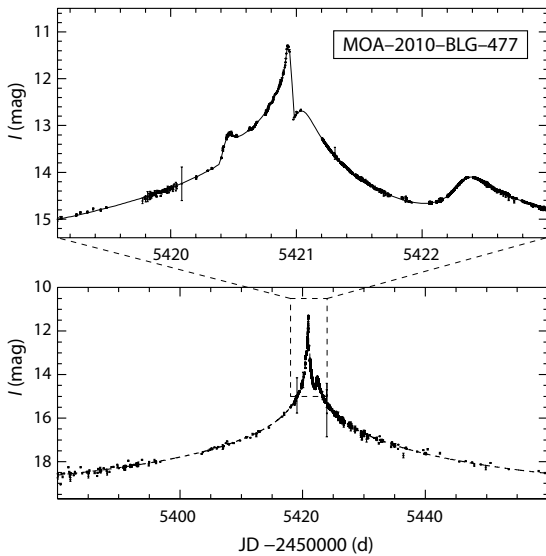


Figure 5.25: Light curve of the microlensing event MOA-2010-BLG-477. The upper panel shows the enlargement of the region of perturbation near the peak of the light curve. The model light curve corresponds to the best-fit solution considering both parallax and orbital motion. In the original figure, data from different observatories are distinguished by colour. From Bachelet et al. (2012b, Figure 2), by permission of IOP Publishing/AAS.

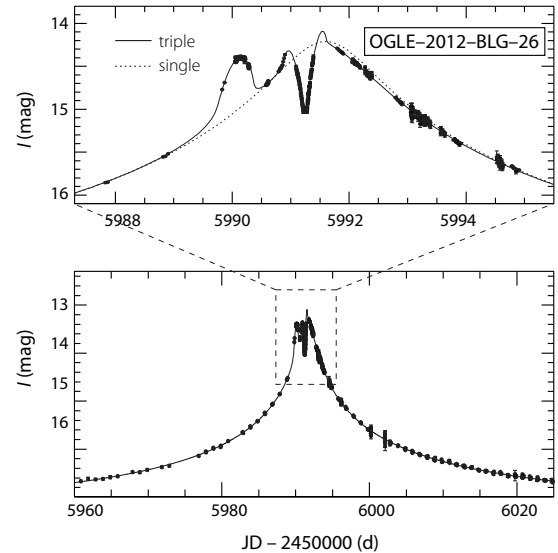


Figure 5.26: Light curve of the microlensing event OGLE-2012-BLG-26. The upper panel shows the enlargement of the region of perturbation near the peak of the light curve. The model light curve corresponds to the best-fit solution considering both parallax and orbital motion. In the original figure, data from different observatories are distinguished by colour. From Han et al. (2013b, Figure 1), by permission of IOP Publishing/AAS.

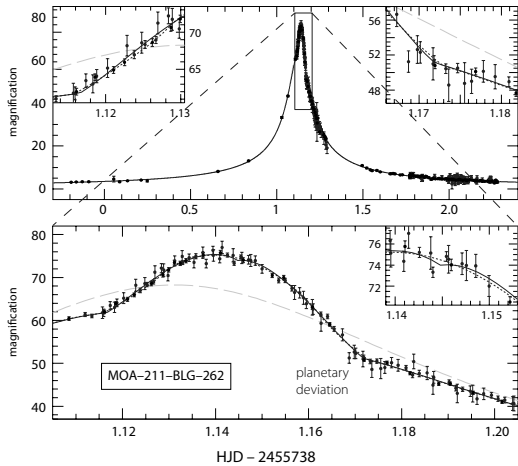


Figure 5.27: The light curve of MOA-211-BLG-262 with data from the MOA 1.8-m, Mt John, Canopus, CTIO, OGLE, and Faulkes South. The long-dashed curve corresponds to the best-fit without a planet. The black curve is the best-fit planetary model; the dotted curve is an alternative planetary model with a slightly larger  $\chi^2$ . From Bennett et al. (2014, Figure 1), by permission of IOP Publishing/AAS.

function, with even a small difference in minimum detectable planet mass leading to a large change in the inferred frequency of planetary companions.

These and later combined analyses of microlensing, radial velocity, and high-contrast imaging surveys now point to a consistent distribution of gas giant planets around M dwarfs in the range 0.07–400 au (Montet et al., 2014; Meyer et al., 2017).

**Overall demographics** Although the number of planets detected by microlensing remains currently rather small, the systematic detection and follow-up of lensing events provides the basis of unbiased samples from which the absolute planet frequency can be inferred over a broad range of planet/star mass ratio and projected separation.

Gould et al. (2006b) used the discovery of the first two cold low-mass planets to estimate that  $38_{-22}^{+31}\%$  of stars host cold super-Earths/Neptunes with separations in the range 1.6–4.3 au.

Sumi et al. (2010) used mass ratios of the 10 lensing planets known at the time, along with a simple scaling relation of the detection efficiency with  $q$ , to derive an intrinsic mass function of planets beyond the snow line of  $dN/dq \propto q^{-1.68 \pm 0.20}$ , implying that cold Neptunes/super-Earths ( $q \sim 5 \times 10^{-5}$ ) are  $7_{-3}^{+6}$  times more common than cold Jupiters ( $q \sim 10^{-3}$ ).

Gould et al. (2010b) selected an unbiased sample of 13 high-magnification events ( $A > 200$ ) between 2005–2008 (out of more than 5000 events known at that time). The host stars have a typical mass  $M_\star \sim 0.5M_\odot$ , with maximum planet detection sensitivity corresponding to

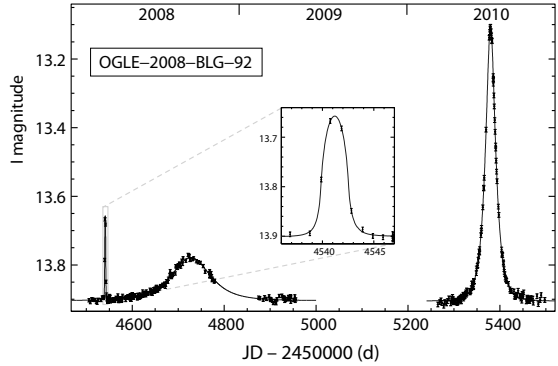


Figure 5.28: Light curve of the OGLE-2008-BLG-92 circumpriary planetary microlensing event. The planet and primary events were detected in the OGLE-III data from 2008, while the secondary event was discovered in the OGLE-IV data from 2010. The model fit is shown by the curved line. From Poleski et al. (2014a, Figure 1), by permission of IOP Publishing/AAS.

deprojected separations roughly three times that of the snow line. At the mean mass ratio  $q = 5 \times 10^{-4}$  they derived a frequency distribution

$$\frac{d^2 N_p}{d \log q d \log d} = (0.36 \pm 0.15) \text{ dex}^{-2}, \quad (5.49)$$

with no significant deviation from a flat (Öpik's law) distribution in  $\log d$ .

Their inferred planet frequency is a factor 7 larger than that derived from Doppler studies at a factor  $\sim 25$  smaller star–planet separations (i.e.,  $P \sim 2 - 2000$  d). They argued that the difference is nevertheless consistent with the extrapolation from Doppler studies, suggesting a universal separation distribution across a factor 100 in star–planet distance, 100 in mass ratio, and factor two in host star mass.

If all planetary systems were solar system analogues, their sample would have yielded 18 planets (11.4 Jupiters, 6.4 Saturns, 0.3 Uranus, 0.2 Neptunes) including 6 systems with two or more planets. This compares with six planets, including one two-planet system, observed. This in turn implies that some 15% of stars host solar system analogues.

Cassan et al. (2012) combined six years of relatively low-magnification ( $A_{\text{max}} \leq 50$ ) events (resulting in three detections), with the mostly independent results from Sumi et al. (2010) and Gould et al. (2010b), to estimate a power-law mass function

$$\frac{d^2 N_p}{d \log a d \log M_p} = 10^{-0.62 \pm 0.22} \left( \frac{M_p}{M_{\text{Saturn}}} \right)^{-0.73 \pm 0.17}. \quad (5.50)$$

This implies an expectation value of  $\langle N_p \rangle = 1.6_{-0.9}^{+0.7}$  planets per star in the range 0.5–10 au and  $5M_\oplus - 10M_J$ . Some key results are shown in Figure 5.30.



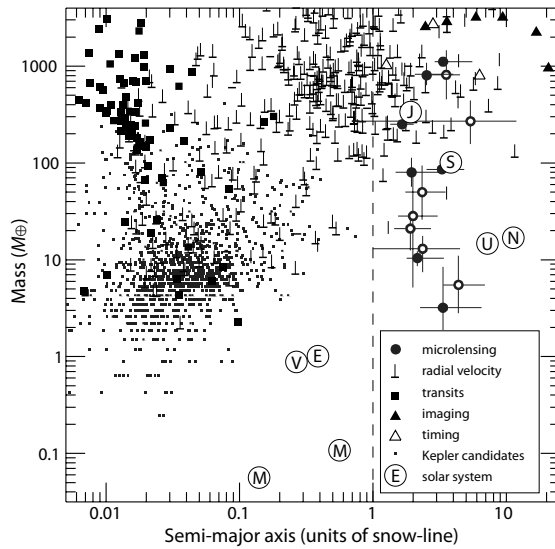


Figure 5.29: Exoplanet mass versus semi-major axis normalised to the snow line,  $a/a_{\text{sl}}$  (box, page 565), according to discovery method. Microlensing planets indicated by open circles have  $M_p$  and  $a$  estimated from a Bayesian analysis. From Muraki et al. (2011, Figure 7), by permission of IOP Publishing/AAS.

**Microlensing, radial velocity and imaging** Clanton & Gaudi (2016) presented a synthesis of three independent detection methods using five different exoplanet surveys [radial velocities: CPS (Johnson et al., 2010d), HARPS-S (Bonfils et al., 2013a), CPS/TRENDS (Montet et al., 2014); microlensing: Gould et al., 2010b); and direct imaging: PALMS (Bowler et al., 2015)] to assess the joint demographics of planets on orbits  $a > 2$  au around single M dwarfs. With a power-law distribution function

$$\frac{d^2 N_p}{d \log a d \log M_p} = A \left( \frac{M_p}{M_{\text{Saturn}}} \right)^\alpha \left( \frac{a}{2.5 \text{ au}} \right)^\beta, \quad (5.51)$$

and with an outer cut-off radius of the separation function,  $a_{\text{out}}$ , they derived  $\alpha = -0.86^{+0.20}_{-0.19}$ ,  $\beta = 1.1^{+1.9}_{-1.4}$ ,  $A = 0.21^{+0.20}_{-0.15} \text{ dex}^{-2}$ , and  $a_{\text{out}} = 10^{+26}_{-4.7} \text{ au}$ . As they stress, these values are consistent with all current knowledge of planets on orbits  $\geq 2$  au around single M stars.

Their study demonstrates that while each individual survey can only constrain certain parameter combinations, a global analysis establishes the existence of a single planet population consistent with them all. For example, the microlensing surveys tightly constrain  $\alpha$  and  $A$ . With these fixed, additional results from CPS/TRENDS place a lower bound on  $\beta$  and  $a_{\text{out}}$ .

Overall, results assuming ‘hot-start’ models (given above) are marginally more constraining than ‘cold-start’ (§10.5.1). Their results also demonstrate that the slope of the mass function heavily favours low-mass planets, with constraints from the imaging surveys dominated by their most sensitive observations.

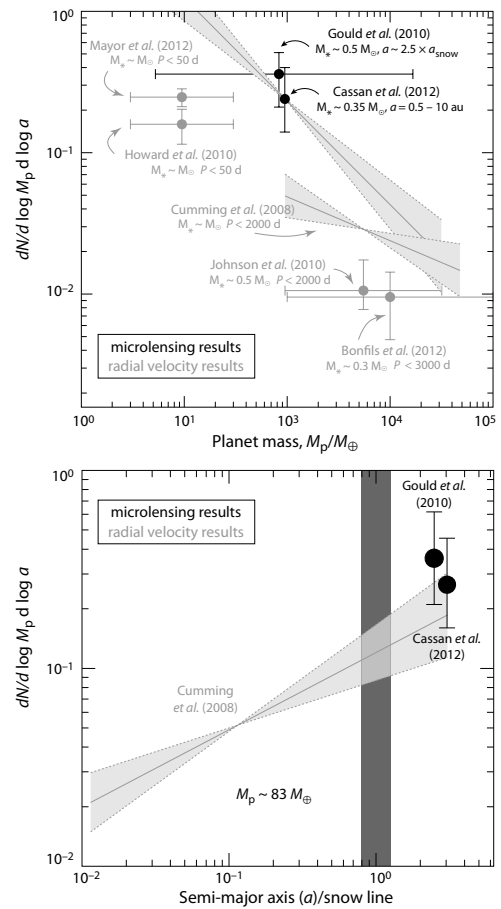


Figure 5.30: Planet frequencies from microlensing (black font) and radial velocity (grey font) samples. (a) Frequencies versus  $M_p$ , for various ranges of  $a$ . Three of the radial velocity samples contain mainly  $\sim 1 M_\odot$  hosts (Cumming et al., 2008; Howard et al., 2010b; Mayor et al., 2011). The others (Johnson et al., 2010d; Bonfils et al., 2013a) contain M dwarf hosts (0.3–0.5  $M_\odot$ ), so not directly comparable to the microlens samples. Shaded regions define power-law extrapolations (Cassan et al., 2012; Cumming et al., 2008). (b) Frequencies as a function of  $a$ , in units of the snow line, assumed to be 2.7 ( $M/M_\odot$ ) au. The Cassan et al. (2012) and Cumming et al. (2008) frequencies are normalised to the typical planet mass of the Gould et al. (2010b) sample,  $\sim 83 M_\oplus$ . From Gaudi (2012, Figure 8), by permission, Annual Reviews ©2012.

Undoubtedly, the true planet distribution function is more complicated, with breaks in mass and semi-major axis, and possibly multiple power-law slopes. The results nonetheless represent an important step in establishing an overall planetary mass function (§10.13.2).

**Free-floating objects** From an analysis of the first two years of MOA-II Galactic bulge data (from 2006–2007), Sumi et al. (2011) found a statistical excess of 10 events with  $t_E < 2$  d (Figure 5.31). Although  $t_E \propto M_L^{0.5}$  (Equation 5.18), these short-duration events cannot immedi-

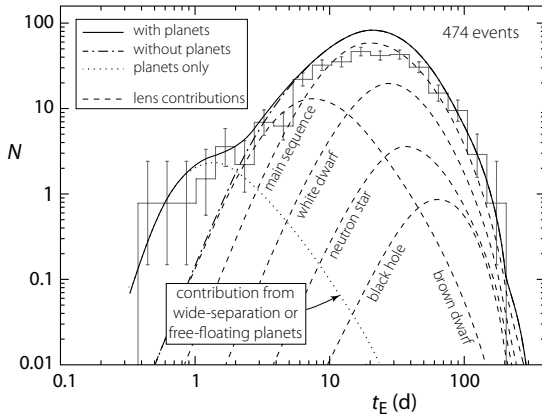


Figure 5.31: Observed and theoretical distributions of the event time scale,  $t_E$ . The histogram is the observed distribution of 474 lensing events from MOA during 2006–2007. Best-fit models are for a power-law mass function, assuming that stars initially above  $1M_{\odot}$  have evolved into stellar remnants (white dwarfs, neutron stars or black holes depending on the initial mass). Lines show the stellar, stellar remnant and brown dwarf populations (long-dashed), the planet-mass population (dotted), and their sum (solid). An excess of events with  $t_E \sim 2$  d may suggest a population of wide-separation or free-floating planet-mass objects (although see Mróz et al., 2017c). From Gaudi (2012, Figure 3b), by permission, Annual Reviews ©2012.

ately be attributed to planetary mass objects, since even at fixed lens mass  $M_L$  and source distance  $D_S$ , the large range of lens distances and lens–source relative velocities results in a large range of time scales (§5.3.8).

Statistically, the distribution of event time scales is expected to show asymptotic power-law tails (Mao & Paczyński, 1996) of the form  $d\Gamma/dt_E \propto t_E^3$  for small  $t_E$  (from lenses close to the observer or source), and  $\propto t_E^{-3}$  for large  $t_E$  (due to events in which the projected velocity between the lens and source is small). The additional feature in the time scale distribution near  $t_E \sim 2$  d does not conform to the expected distribution. Showing no indications of other associated lenses, it therefore suggests a feature in the underlying mass function due to a population of isolated, free-floating, planet-mass objects. Their number is comparable to the number of bound planets found by microlensing, and with an abundance of  $1.8^{+1.7}_{-0.8}$  per main sequence star. A similar fraction was found by Clanton & Gaudi (2017).

These planetary mass objects are isolated in the sense that there is no host star detected in the lensing data. Lower limits on the projected separation between the planet and a possible host depend on the latter’s Einstein radius, and are estimated to range from  $2.4 - 15.0 R_E$  (7–45 au), assuming typical host star masses and random orientations (Bennett et al., 2012).

The Gemini Deep Planet Survey (Lafrenière et al., 2007a) has set upper limits on the number of stars with  $\sim 1M_J$  planets at  $a \sim 10$ –500 au, with the tightest limits

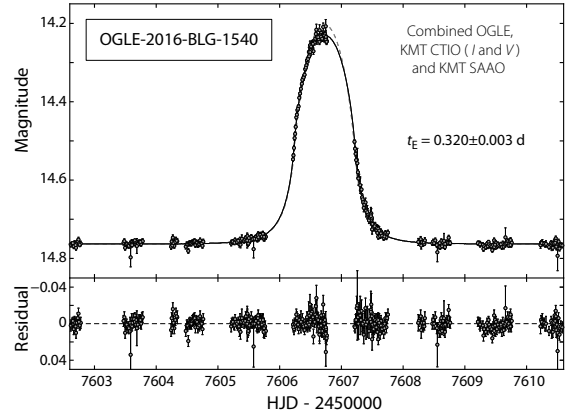


Figure 5.32: The free-floating event OGLE-2016-BLG-1540. The event is of very short duration ( $t_E = 0.320 \pm 0.003$  d), and the prominent finite-source effects yields an estimate of the lens mass  $M_P = 35M_{\oplus}$  ( $0.1 \text{ mas}/\varpi_{\text{rel}}$ ), somewhere between that of Neptune and Saturn (with an uncertainty due the relative parallax error). The light curve is well described by a finite-source point-lens model (solid line in I-band, dashed line in V-band, which differ due to the different limb-darkening profile). The original figure distinguishes the OGLE, KMT CTIO, and KMT SAO observations. From Mróz et al. (2018, Figure 1), by permission of IOP Publishing/AAS.

of  $< 30\%$  of stars in the range  $a \sim 50$ –250 au. Sumi et al. (2011) therefore estimated that less than 40% of stars have a  $\sim 1M_J$  planet in the range  $10 < a < 500$  au, assuming a uniform distribution in  $\log a$ . They concluded that  $\geq 75\%$  of these objects are not bound to any star.

The constraints from imaging require consolidation (Quanz et al., 2012c), and it remains possible that these ‘isolated’ planets may nonetheless represent bound planets in wide orbits (Nagasawa & Ida, 2011; Wambsganss, 2011; Quanz et al., 2012c), although this was excluded by Clanton & Gaudi (2017). If so, they may have formed closer to their host stars (near the snow line) and moved outwards by migration, or through an *in situ* formation mechanism such as gravitational instability (Bowler et al., 2011). Although planet-mass objects are now being found by infrared imaging surveys down to perhaps  $4 - 7M_J$  (§9.9), they do not yet reach to  $\sim 1M_J$  where the microlensing signal is seen.

The population of free-floating or wide-separation planets remains poorly understood. This was underlined by Mróz et al. (2017c) who, from a more extensive microlensing sample, six times larger from discoveries in 2010–15, failed to confirm the excess of events in the 1–2 d range found by Sumi et al. (2011). They did detect a few possible ultrashort-timescale events ( $< 0.4$  d), which may indicate the existence of Earth-mass and super-Earth-mass free-floating planets, more in line with predictions from planet-formation theories.

Some 1.4–7.9 events for the Kepler/K2 microlensing Campaign 9 were predicted by Penny et al. (2017).

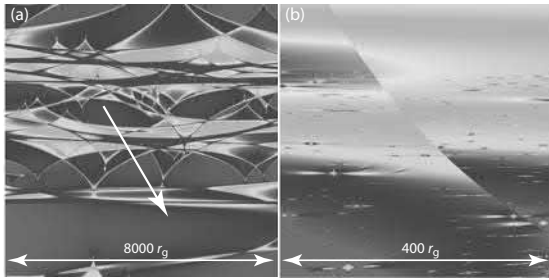


Figure 5.33: Microlensing magnification maps of RX J1131–1231A with dimensions in units of  $r_g = GM/c^2$ : (a) with stars only, and showing a random path of a compact source moving across the map with a 10-yr duration. The probability for a caustic to land on the source region is only a few percent, significantly below the observed rate of  $\sim 30\%$ ; (b) with an additional planet population for a planet mass fraction  $\alpha_{\text{pl}} = 0.001$ , showing a much higher caustic density. From Dai & Guerras (2018, Figure 2), by permission of IOP Publishing/AAS.

**A Neptune-mass free-floating candidate** After the nominal cut-off date for this review, a free-floating candidate of mass  $35M_{\oplus}$  ( $0.1 \text{ mas}/\omega_{\text{rel}}$ ) has been reported (Mróz et al., 2018). Previous free-floating planet candidates were based only on the very short event time scale, without a direct measurement of the angular Einstein ring size. In contrast, OGLE–2016–BLG–1540 was not only an ultra-short event, with  $t_E = 0.320 \pm 0.003 \text{ d}$ , but also allowed a direct size estimate, from its angular Einstein ring size, due to the fortuitous fact that the source was a giant star (Figure 5.32).

**Quasar microlensing** The connection between this population, and the population of planetary mass microlensing objects (MACHOs) inferred from early quasar microlensing studies (Schild, 1996; Colley & Schild, 2003) is discussed by Schild et al. (2012). Constraints on the mass of free-floating planets in the globular cluster M22 were given by Sahu et al. (2001), but the events were questioned (Gaudi, 2002), and later retracted (Sahu et al., 2002). Gil-Merino & Lewis (2005) investigated suggestions that uncorrelated variability in the gravitationally-lensed quasar QSO 2237+0305 (the Einstein Cross) could be attributed to a microlens population of free-floating planets, and argued that such conclusions are flawed.

Dai & Guerras (2018) evaluated quasar microlensing close to the event horizon of the supermassive black hole of the background quasar ( $z = 0.295$ ) in the quadruple-lensed system RX J1131–1231. From 38 Chandra X-ray observations over 10 years, they modeled the energy shifts in the Fe  $K\alpha$  line, and inferred a population of unbound planets with a total mass fraction  $> 0.0001M_{\text{halo}}$ , equivalent to 2000 objects ranging from Moon to Jupiter mass per main sequence star (Figure 5.33).

### 5.10.3 Limitations and strengths

In the early days of microlensing planet searches, the rarity of the phenomenon was a barrier to progress, with hundreds of millions of stars having to be monitored to detect the few that might be microlensing at any time. Even then, planetary deviations in the light curves are short-lived, of order hours or days, and the most crucial features were easily missed. Today, observational programmes are delivering significant numbers of planetary candidates with good event coverage.

Compounding the task of interpretation, a microlensed planet, once found, will typically be very distant (of order a few kpc). The distance itself may be difficult to estimate without additional constraints such as the microlens parallax, or unless the host star is visible.

While planetary deviations captured in microlensing light curves never repeat, at least on any relevant time scale due to the rarity of suitable alignments, this has not proven to be an insurmountable barrier to interpretation. Many other astrophysical phenomena (supernovae,  $\gamma$ -ray bursts, detailed accretion events) never repeat in the same object, and plausibility is more a matter of signal-to-noise and repeatability as a class.

Alongside these difficulties are a number of important strengths, which complement other detection methods, and which should be substantially augmented by space-based measurements in the future.

As discussed in the previous sections, these include: (a) sensitivity to low-mass planets, down to  $M_{\oplus}$  and below; (b) sensitivity to lens systems anywhere along the sight line to the Galactic bulge, with a maximum sensitivity for a lens position roughly halfway to the source; (c) detections largely unbiased in terms of host star properties, e.g. spectral type or activity, such that planets and their host stars should be found in proportion to their true occurrence in the Galaxy disk; (d) peak sensitivity beyond the snow line (box, page 565), viz., further out in orbital radius than typically probed by radial velocity and transit measurements; (e) the capability of detecting much wider separation, or even free-floating planet mass bodies; (f) detectability of multiple planets, and orbital motion, either via very high magnification events with sufficiently small impact parameters passing the central caustic, or through the chance passage through two or more planetary caustics.



# Transits

THE FIRST TRANSIT of an extrasolar planet was observed in 1999, as a result of photometric monitoring of the known close-in ‘hot Jupiter’ system HD 209458. Other systems discovered from radial velocity surveys were subsequently monitored to look for possible transits. Dedicated surveys from the ground, and subsequently from space, were quickly set up to carry out ‘blind searches’ for new planets from their periodic transit signatures alone.

Transiting planets are of particular importance because their light curves provide an estimate of their radii. Densities follow if their mass can also be estimated, giving a first estimate of their composition. Further probing of the planet’s structural and atmospheric properties are accessible from photometry and spectroscopy during the transit, and during the secondary eclipse when the planet passes behind the star.

By the end of 2017, nearly 3000 transiting planets had been discovered, almost 2500 from the Kepler space observatory, the dedicated transit search mission launched in 2009 which has transformed the field.

The combination of a relatively small number of bright and well-observable transiting systems discovered from the ground-based surveys, notably HAT and WASP, and the substantial numbers of close-orbiting multi-planet systems discovered by Kepler, has resulted in a rich variety of exoplanetary systems displaying a wide range of physical properties and conditions.

## 6.1 Introduction

**Objectives** Given a suitable alignment geometry, light from the host star is attenuated by the transit of a planet across its disk, with the effect repeating at the orbital period. The probability of observing such a transit for any given star, seen from a random direction and at a random time, is extremely small.

The effect being sought is also small: a planet with  $R \sim R_J$  transiting a star of  $1R_\odot$  results in a drop of the star flux of  $(\Delta F/F) \simeq 1.1 \times 10^{-2}$ , or around 0.01 mag. For planets of Earth or Mars radius,  $\Delta F \simeq 8.4 \times 10^{-5}$  and  $3 \times 10^{-5}$  respectively.

Depths of up to 7% might occur for M dwarfs (Haghighipour et al., 2010), and significantly more for planets around white dwarfs (Drake et al., 2010; Agol, 2011; Faedi et al., 2011b).

**Transit probability** The probability for a randomly-oriented planet on a circular orbit to be favourably aligned for a transit is (Borucki & Summers, 1984)

$$p = \frac{R_\star}{a} \simeq 0.005 \left( \frac{R_\star}{R_\odot} \right) \left( \frac{a}{1 \text{ au}} \right)^{-1}, \quad (6.1)$$

given by the solid angle on the sphere swept out by a planet’s shadow (a more detailed development, accounting for secondary eclipses, the planet size, grazing transits, and elliptical orbits, is given in Section 6.13). Evaluation of  $i$  and  $p$  for realistic cases demonstrates that transits only occur for  $i \simeq 90^\circ$ , while  $p$  is very small. The transit probability is independent of star distance, but the corresponding photometric accuracy decreases.

**First discovery** The first exoplanet transit, HD 209458, was observed by Henry et al. (1999, 2000) and independently by Charbonneau et al. (2000) from photometric monitoring of a known radial-velocity system. Charbonneau et al. (2000) observed two transits (Figure 6.1), of duration 2.5 h and a depth of 1.5%, at an interval consistent with the known orbit. It gave the first confirmation that ‘hot Jupiters’, Jupiter-mass planets in very close orbits about their host stars, have radii and densities comparable to the gas-giants of the solar system.

Since then, the number of known transiting planets has grown rapidly. A few have been found in the same way as HD 209458 b, by photometric follow-up of known Doppler planets at times of inferior conjunction. Many more have been found using small-aperture, wide-field imaging systems based on commercial optics of modest cost, surveying the entire sky for prominent transits of the brightest stars. Launch of the space missions CoRoT in 2006, and Kepler in 2009, has led to the discovery and characterisation of many thousands. Together, these observations have provided a wealth of information on exoplanet properties, planetary system architectures, and associated physical phenomena.

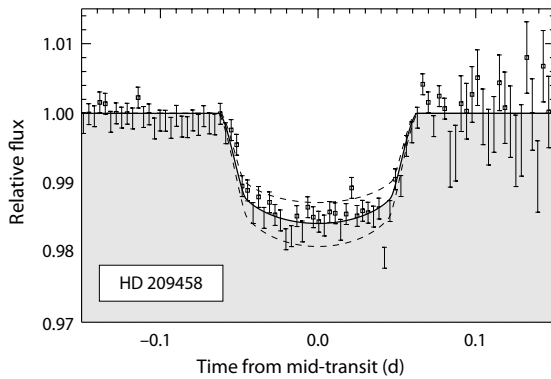


Figure 6.1: The first detected transiting exoplanet, HD 209458, showing the measured flux versus time. Measurement noise increases to the right due to increasing atmospheric air mass. It may be compared with the subsequent space-based light curve observed by HST (Figure 6.15). From Charbonneau et al. (2000, Figure 2), by permission of IOP Publishing/AAS.

**Ground versus space** Ground-based photometry to better than  $\sim 0.1\%$  accuracy is complicated by variable atmospheric extinction, while scintillation, the rapidly varying turbulent refocusing of rays passing through the atmosphere, imposes limits at  $\sim 0.01\%$ . Extension of the transit method to space, where very long uninterrupted observations can be made above the Earth's atmosphere, is therefore particularly important.

Nearly continuous observations from months to years allows the discovery and characterisation of transiting exoplanets to be extended to those with much longer orbital periods than can be discovered from the ground. The excellent photometric precision above the atmosphere allows the detection of transit depths of a few times  $10^{-4}$ , extending detectable exoplanet radii down to  $\sim 1R_{\oplus}$ , or even smaller. High-precision measurements from space also make it easier to detect the tiny signatures (less than  $10^{-4}$ ) of the reflected and radiated light from the exoplanet, as well as its atmospheric features. Space instruments can also access wavelength regions, notably the near infrared, largely inaccessible from the ground, which are important for studying their atmospheric transmission and emission spectra.

Various space missions have advanced the discovery and understanding of transiting systems (Hatzes, 2014b). These include the dedicated transit missions CoRoT and Kepler, along with additional characterisation from MOST, HST, Spitzer, and Hipparcos. In the near future, Gaia, TESS, PLATO and others are again expected to advance the field substantially.

**Overview of insights from transits** From the dip in the stellar brightness during the transit, the radius of the planet can be estimated. When combined with the mass determination, for example from spectroscopic Doppler measurements, this can be used to obtain the planet's

**Transits and eclipses:** An eclipse is the (partial) obscuration of one celestial body by another. When of very different angular size, the term *transit* refers to the smaller (here the planet) moving in front of the larger (the star), viz. at the time of inferior conjunction; an occultation, or *secondary eclipse*, refers to the planet passing behind the star (superior conjunction). 'First contact' (see Figure 6.26, §6.13) denotes the start of the transit, when the projected outer rim of the planet makes contact with the projected outer rim of the star, and similarly for fourth contact on exit. Second and third contact are the times when the projected planet lies just inside the projected rim of the star, on ingress and egress. Grazing transits and secondary eclipses occur when the projections never fully overlap (§6.14.14).

mean density. The density gives the first hints about the internal structure of the planet.

It is also possible to characterise the atmosphere of a transiting exoplanet using measurements taken at different points in its orbit. These measurements include spectra taken during transit, photometric variations throughout the orbit, and secondary eclipse data.

During the transit, some of the starlight is absorbed by the planet's atmosphere, which therefore imprints itself on the stellar spectrum giving insight into its composition through *transit spectroscopy*.

As the planet orbits, the illuminated portion of the sphere as seen from Earth changes, resulting in light variations (the *brightness phase curve*) throughout the orbit, from which the brightness distribution on the planet may be derived. High-precision photometric measurements can also detect other subtle variations in the light curve of the star, including *ellipsoidal variations* resulting from the distortion of the figure of the star due to tides raised by the planet, and *relativistic beaming* resulting from the star's reflex motion about the system barycentre. Both phenomena can provide independent estimates of the planet mass.

Finally, when the planet disappears behind the star, its reflected and radiated light is blocked. Phase and secondary eclipse measurements provide information about the brightness temperature, the planetary albedo, and the exoplanet's spectral features.

**Exoplanet transit data** Two primary online catalogues provide an up-to-date compilation of known exoplanets, including transiting planets, and their associated properties: the NASA Exoplanet Archive, and the Extrasolar Planets Encyclopedia. Others maintain a critical compilation of exoplanet orbits, as well as other information on exoplanet transits. Some of the key online resources are given in Table 1.4.

Appendix D lists the transiting systems known by the end of 2017, with concise literature notes for each. This provides an at-a-glance indication of the 'importance' of individual discoveries, a chronological summary of advances, and an entry to the more detailed literature.

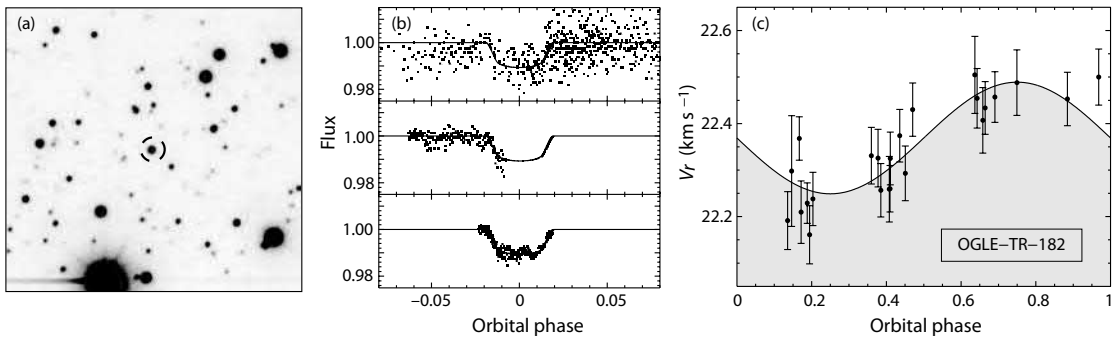


Figure 6.2: OGLE-TR-182 ( $P = 3.98$  d,  $I = 15.9$  mag), representative of the state-of-the-art in OGLE transit searches: (a) VLT I-band image (50 arcmin square field); (b) light curves from the OGLE telescope (top), and VLT-FORS1 (bottom two); (c) radial velocity from VLT-FLAMES/UVES. From Pont et al. (2008b, Figures 1–3), reproduced with permission © ESO.

## 6.2 Transit searches: wide angle

Almost all transiting planets, except for the first few observed around Doppler-discovered systems, have been found from dedicated wide-angle searches. Since there is little to indicate *a priori* which stars may have planets, which of those that do might be oriented favourably for a transit to be observed, and when or how frequently such transits may occur, surveys simply monitor large numbers of stars, simultaneously and for long periods of time, searching for the tiny periodic drops in intensity that might be due to transiting planets.

Initially, there was considerable optimism of finding large numbers of planets from dedicated transit searches (e.g. Horne, 2001; Gillon et al., 2005). But stringent observational requirements quickly became evident: the need for dedicated telescopes, the highest photometric precision, stable instrumentation with low systematic noise, and the handling of large number of false-positives, either due to isolated or blended eclipsing binary systems, or to noise (Brown, 2003). This in turn called for optimal follow-up strategies, with access to high-accuracy spectroscopy (Tingley & Sackett, 2005).

**Increasing discoveries** A rise in discovery rate since 2005 followed as techniques were mastered: after just three discoveries to the end of 2003, eight were found in 2004–05, 26 in 2006–07, and 27 in 2008–09. These included a number of transiting (non-lensed) planets from ongoing microlensing surveys (Figure 6.2).

By the end of 2017, discoveries from HAT and WASP, and from space with CoRoT and especially with Kepler, total nearly 3000 planets, with other Kepler candidates awaiting confirmation. Other dedicated space missions are in advanced stages of development.

Search efficiency is now such that transiting planets are occasionally found independently from different surveys, e.g. WASP-11 b which was independently discovered as HAT-P-10 b, and HAT-P-14 b independently as WASP-27 b. A full listing is given in Appendix D.

**Survey yields** Predicting survey yields, taking account of telescope size, exposure, wavelength, window function, planet frequencies, stellar distributions and interstellar extinction, has been tackled in various studies (e.g. Beatty & Gaudi, 2008; Heller et al., 2009; von Braun et al., 2009), including the gains to be made by combining the various survey results (Fleming et al., 2008).

Although large apertures are not required for discovery instruments, large numbers of stars must be monitored to capture the small fraction whose planetary orbits are both suitably aligned with respect to the line-of-sight ( $i \approx 90^\circ$ ) and, at the time, transiting.

Practical ground-based searches vary in their details, but follow broadly similar principles: tens of thousands of relatively bright stars ( $V \lesssim 13$  mag) are monitored over weeks or months, possible transits identified in the photometric time series, and stellar binaries eliminated. Confirmation of the planetary nature of the companion is generally claimed only after more detailed verification, generally based on radial velocity observations.

More quantitatively, statistics suggest that  $\sim 1.7\%$  of dwarf stars host planets that could be detected by ground-based surveys such as HAT and WASP, viz.  $R_p = 3 - 32R_\oplus$  and  $P < 20$  d (Mayor et al., 2009b; Howard et al., 2010b, 2012b). This reduces to  $\sim 0.1\%$  when combined with the geometric transit probability (Equation 6.1), and to fewer than 1 in 2000 when further accounting for a 40% occurrence rate of A5–M5 dwarfs in surveys with  $r \lesssim 12$  mag (to allow spectroscopic confirmation).

Consequently, the monitoring of tens of thousands of stars at high duty cycle, and homogeneously optimal data quality, is required to achieve a reasonable transiting planet detection yield (Bakos et al., 2013).

The large ground-based transiting surveys HAT and WASP are typically strongly biased towards Jupiter-size planets with  $P \lesssim 5$  d. Only  $\sim 10\%$  of transiting planets discovered from ground have  $M < 0.1M_J$  (dictated by the atmosphere), and only a similar fraction have  $P > 5$  d. The short-period bias is due to the higher geometric

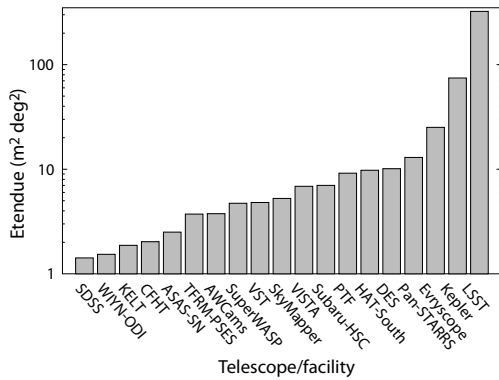


Figure 6.3: The *étendues* of various survey instruments, relevant for bright sources and high-cadence monitoring. The combined field is used for multiple-telescope surveys. Telescopes/facilities not referred to in the text, in the context of exoplanet studies, include: ASAS-SN (All Sky Automated Survey for SuperNovae); DES (Dark Energy Survey); SDSS (Sloan Digital Sky Survey); Subaru-HSC (Subaru Hyper Suprime-Cam); TRFM-PSES (Telescope Fabra ROA Montsec); VST (VLT Survey Telescope); and WIYN-ODI (Kitt Peak WIYN One Degree Imager). From Law et al. (2015, Figure 2), reproduced by permission, Institute of Physics Publishing.

transit probability for short-period orbits (Equation 6.1), to the low duty cycle of single-longitude surveys, and to the relative ease of their radial velocity confirmation.

Space-based surveys, with CoRoT and in particular with Kepler, have led to the discovery of thousands of transiting systems, as a result of their improved photometric accuracy and their near-continuous observations of target stars over months and years.

**Étendue** The rate at which a telescope can survey a volume of space can be quantified by its *étendue*,  $E = A\Omega$ , the product of its effective aperture ( $A$ , typically in  $\text{m}^2$ ) and the solid angle on the sky imaged in a single exposure ( $\Omega$ , typically in  $\text{deg}^2$ ). A comparison of various telescopes is given in Figure 6.3.

**Cadence** Surveys (transit, microlensing, or radial velocity) are also characterised by their *cadence*, essentially the time interval between successive mid-exposures. For observations comprising a sequence of exposures of duration  $t_1$ , each followed by an ‘off-source’ interval  $t_2$ , the cadence is given by  $\Delta t = t_1 + t_2$ , with ‘high-cadence’ implying small  $\Delta t$ .  $t_1$  is determined by factors such as the source brightness and event time scale, with the adopted cadence being a compromise depending on factors such as the expected event duration, detector readout, number of fields being observed, and the resulting data volume. Thus, in prospective surveys searching for transit or microlensing candidates,  $t_2$  may include intervals devoted to other objects or sky regions, with  $t_1 \ll t_2$ . For high-quality observations of a specific object,  $t_2$  may be the minimum value consistent with detector readout requirements, such that  $t_1 \gg t_2$ .

For most transit surveys the times adopted in a light curve are the mid-exposure times, but for radial velocity surveys using exposure meters (§2.4.3), the adopted time may be flux-weighted. Cadence is distinct from integration time: while the latter sets a minimum achievable cadence, there is typically some overhead when the camera is not integrating, while in some cases (e.g. Kepler) multiple ‘exposures’ are combined in a single cadence.

Cadences are generally non-uniform, with no clear convention for survey characterisation in terms of, e.g., median, mode, or minimum achieved cadences. Space-based surveys (CoRoT, Kepler, K2) typically have much closer to uniform cadence than ground-based surveys, although even these have non-uniform cadence in practice. Considerations that determine the cadence adopted for a given survey include the readout time of the detector (the longer the readout, the more incentive there is to use longer exposure times, and thus to have a longer cadence), detector saturation, and data transmission bandwidth (related to data volume).

HAT uses a cadence of 3.5 min (HAT-North) or 4 min (HAT-South). WASP typically observes a dozen fields per night across a strip of constant declination, with two 30-s exposures taken at each visit, and a typical cadence of  $\sim 10$  min.

Kepler provides two options (§6.6.1), either short cadence used for asteroseismology of solar-like stars and transit timing measurements where a higher (58.9 s) sampling rate is crucial (Gilliland et al., 2010), or long cadence (29.4 min) used for most of the core mission science, largely to reduce telemetry rates.

**Outline of the data processing** In the first reduction step of ground surveys such as HAT and SuperWASP, automatic field recognition matches observed stars to a reference catalogue (Tycho 2 or 2MASS), providing an astrometric solution to 1–3 arcsec (Pál & Bakos, 2006).

Magnitudes at each epoch are based on the optimised techniques of aperture photometry (Gilliland & Brown, 1988; Kjeldsen & Frandsen, 1992; Everett & Howell, 2001), augmented by difference imaging (Alard & Lupton, 1998). Error sources include photon noise, atmospheric effects including scintillation (§6.11), and differential extinction. Photometric zero-points are determined with reference to USNO-B1.0 or 2MASS.

Correct handling of non-Gaussian noise is critical for the detection of transits depths of only a few mmag. Typically at the end an observing season, trends and correlated systematics are removed from the entire data set, e.g. using SysRem (Tamuz et al., 2005; Smith et al., 2006), the trend-fitting algorithm TEA (Kovács et al., 2005) or external parameter decorrelation, EPD (Bakos et al., 2010). An empirically-determined variance can be added to match observed noise properties to facilitate statistical analyses (e.g. Collier Cameron et al., 2006).

**Candidate identification** Searches typically adopt a modified box-least squares algorithm (Kovács et al., 2002) with a coarse search grid to identify epoch, period, depth and duration of the strongest signals, which can then be refined using transit profile models (Protopapas et al., 2005). Literature on search techniques and their comparison includes, e.g., Aigrain & Favata 2002; Tingley 2003; Aigrain & Irwin 2004; Tingley 2004;



**Historical context and early studies:** In the mid-19th century, the principle of detection of exoplanets by the transit method was already noted by Lardner (1851, Chapter XXVII). As quoted by Howell et al. (1999), amongst five suggestions to explain periodic variable stars, Lardner stated '*Periodical obscuration or total disappearance of the star may arise from transits of the star by its attendant planets.*'

In 1938, D. Belorizky from Marseille Observatory considered the effects of a Jupiter-mass planet orbiting another star on both the radial velocity and photometric signature (Belorizky, 1938), and stated that (the italics are the author's) 'Toutes ces considérations nous incitent à penser que c'est peut-être dans la photométrie des étoiles avec une précision de 1/100 de magnitude que se trouve le moyen de découvrir *l'existence d'autres systèmes planétaires.*' [These considerations suggest that stellar photometry with 0.01 mag precision will provide the means of discovering *the existence of other planetary systems.*] As of the end of 2017, this prescient paper had just two ADS citations (viz. Mayor et al., 2014; Briot et al., 2015).

The short paper by Struve (1952) is more frequently cited as the first drawing attention to the transit method to detect exoplanets. It also contains his somewhat cryptic remark that '*It is not unreasonable that a planet might exist at a distance of 1/50 astronomical unit, or about 3 000 000 km. Its period around a star of solar mass would then be about 1 day.*'

Discovery prospects were developed by Rosenblatt (1971), who considered the event's colour signature due to limb darkening, along with the effects of stellar noise (variability, flares, and sun spots) and Earth's atmosphere (air mass, absorption bands, seeing, and scintillation). Further developments were brought by Borucki & Summers (1984) and Borucki et al. (1985).

Based on the radial velocity measurements of Latham et al. (1989), Robinson et al. (1990) described HD 114762 as a good candidate for a planetary-mass object, and searched for eclipses of the host star by the companion. Finding no eclipses with a depth greater than 0.01 mag, they concluded that the orbit inclination was less than  $89^\circ$ .

Even before the detection of the first exoplanet in 1995, and before the detection of the first transiting planet in 1999, the method was considered as one of the most promising means of detecting planets with  $M_p \ll M_J$ , with the detection of Earth-class (and hence habitable) planets quickly seen as being within its capabilities (Schneider & Chevreton, 1990; Hale & Doyle, 1994; Schneider, 1994b; Heacox, 1996; Janes, 1996; Schneider, 1996; Deeg, 1998; Sartoretti & Schneider, 1999).

Moutou et al. 2005b; Weldrake & Sackett 2005; Collier Cameron et al. 2006; Schwarzenberg-Czerny & Beaulieu 2006; Régulo et al. 2007; Carpano & Fridlund 2008; Ford et al. 2008b; Carter & Winn 2009.

**Stellar mass binaries** The identification of possible transiting planets is complicated by the presence of much larger numbers of stellar mass binaries (Willems et al., 2006). Ellipsoidal (binary star) variables are rejected from the out-of-transit light curves, and probable giants can be eliminated on the basis of their reduced proper motions (e.g. using 2MASS, Collier Cameron et al., 2007b). A first estimate of stellar mass and radius, and planet radius and impact parameter, are then derived from light curve models using an appropriate limb darkening description. Possible transiting objects are then subjected to more careful photometry on the ground to exclude faint background eclipsing binaries.

**Candidate confirmation** Only the most promising candidates are finally subjected to radial velocity follow-up measurements: a small radial velocity amplitude, combined with the transit signature implying that the inclination  $i \approx 90^\circ$ , together ruling out stellar mass eclipsing binaries with small inclination. Double-lined (stellar mass) binaries and fast rotators can typically be rejected after a single observation, narrow single-lined stellar binaries after a second, while objects with planet-like radial velocity amplitudes are observed until ten or so measurements confirm their substellar mass.

Especially for Kepler, where the many candidates and their relatively faint host preclude large-scale radial-velocity follow-up, other diagnostics have been developed to reject or confirm the candidates (§6.12.5).

**Star and planet parameters** Host star parameters can be determined from the radial velocity observations, e.g. deriving  $T_{\text{eff}}$  and  $\log g$  from diagnostic spectral lines (such as  $H\alpha$ , Na I D and Mg I b), and thereafter  $M_\star$  and  $R_\star$  from appropriate stellar evolutionary models. Planetary radii can then be estimated by a combined fit to the photometric and radial velocity measurements together.

### 6.3 Transit searches: specific targets

In addition to the large-scale blind survey programmes, some searches have concentrated on specific stellar types or environments.

#### 6.3.1 Radial velocity discoveries

A dozen or so exoplanets, originally discovered from radial velocity measurements, have subsequently been found to transit (see accompanying box). A more complete bibliography is given for these in a specific section on transiting planets in Appendix D. These include the bright, well-studied objects HD 189733 and HD 209458.

In turn, at least two radial velocity programmes have focused on short-period giant planets, which are more likely to transit their host star (da Silva et al., 2006).

The ELODIE metallicity-biased programme combines high-precision radial velocities with the 1.93-m telescope of OHP, and high-precision photometry from the 1.20-m telescope, and resulted in the discovery of the transiting HD 189733 b (Bouchy et al., 2005c). Its short period of 2.219 d, and its large transit depth of 3% ( $M \approx 1.15 M_J$ ,  $R \approx 1.26 R_J$ ) make it one of the prime targets for atmospheric studies from the ground, and from space (with HST and Spitzer).

N2K has also discovered one transiting planet using a similar approach: HD 149026 b (Sato et al., 2005a).

In addition to general searches for transits, some programmes (such as TERMS) have given specific attention to planets which are more likely to transit, and to refining their possible transit ephemerides. Further consideration of this topic, in terms of refining *a priori* transit probabilities for eccentric orbits, or including constraints on stellar inclination, is given in Section 6.13.

**Long-period planets** Planets with  $P \geq 10$  d are not easily followed photometrically after radial velocity detection because the geometric transit probability becomes very small, and ground-based surveys which rely on photometry folding rapidly become incomplete.

The [Transitsearch.org](http://Transitsearch.org) network started monitoring these cases in 2002, using small telescopes and amateur participation, based on possible transit predictions (Seagroves et al., 2003; Shankland et al., 2006; Kane, 2007; Kane et al., 2009). The network observed a transit of the high-eccentricity 21-d period HD 17156 b on 2007 September 9–10 (Barbieri et al., 2007), for which the favourable geometry from the radial velocity orbit had given an *a priori* transit probability of 13%, and a transit time predicted to within a few hours.

The 111-d orbital period of HD 80606 b is even more extreme. It was discovered from its radial velocity signature as a giant planet on a highly eccentric orbit ( $4M_J$ ,  $e = 0.93$ ; Naef et al., 2001a). The secondary transit around pericentre was discovered from Spitzer  $8\mu\text{m}$  observations (Laughlin et al., 2009), and the two data sets together implied an orbit inclination  $i \approx 90^\circ$ , and a 15% probability that the planet would transit. With a corresponding transit window predicted for 2009 February 14, three groups independently observed a transit (Moutou et al., 2009a; Fossey et al., 2009; Garcia-Melendo & McCullough, 2009; Hidas et al., 2010).

**Searches with Spitzer** Searching for transits of super Earths discovered from radial velocities poses a challenge because ground-based transit surveys generally lack the sensitivity to detect them. A Spitzer programme to observe five of the most favourable radial velocity-detected super-Earths (GJ 876, HD 1461, HD 7924, HD 156668, and HIP 57274) yielded no evidence for transits in any of their  $4.5\mu\text{m}$  flux light curves (Kammer et al., 2014). Limits on the allowed transit depths and corresponding planet radii could rule out even the most dense and iron-rich compositions. A further programme to search for the transits of 25 HARPS low-mass planets, starting in 2010, has also been unsuccessful, at least for the 19 targets reported so far (Gillon et al., 2010a, 2017a).

### 6.3.2 Open and globular clusters

A significant effort has been devoted to transit searches in Galactic open clusters and, to a lesser extent, in a few globular clusters.

The scientific motivation for these searches includes establishing the effects of stellar density and metallicity on planet occurrence (e.g. Ida et al., 2000; Kobayashi & Ida, 2001; Kenyon & Bromley, 2002a), determining time scales of planet formation and migration, and modeling the effects of stellar encounters on formation and disruption (Fregeau et al., 2006; Malmberg et al., 2007b; Weldrake, 2008; Fragner & Nelson, 2009).

**Open clusters and associations** Several groups have targeted young Galactic open clusters in unsuccessful searches for transiting planets (box, page 159). Some operate under their own acronyms: EXPLORE-OC, Extrasolar Planet Occultation Research/Open Clusters (von Braun et al., 2005); Monitor (Hodgkin et al., 2006); PISCES, Planets in Stellar Clusters Extensive Search (Mochejska et al., 2004); and STEPSS, Survey for Transiting Extrasolar Planets in Stellar Systems (Burke et al., 2004). Typical accuracies are in the range 3–10 mmag.

The Young Exoplanet Transit Initiative (YETI) is a world-wide network monitoring young (2–200 Myr) nearby clusters in a search for young transiting planets (Neuhäuser et al., 2011). Trumpler 37 was observed throughout 2010–11 (Errmann et al., 2013b), and resulted in one false-positive (Errmann et al., 2014b). Their first transiting candidates (two in Trumpler 37, one in 25 Ori) were reported by Errmann et al. (2014a). Other cluster observations reported include IC 348 (Fritzewski et al., 2016) and NGC 7243 (Garai et al., 2016).

The paucity of cluster planets found to date may not be unexpected, given the relatively few stars per cluster (Aigrain & Pont, 2007; Weldrake, 2008). Pepper & Gaudi (2005, 2006) argued that surveys of the nearest and richest open clusters, with moderate instruments over more than 20 nights (e.g. a Pan-STARRS survey of the Hyades and Praesepe), do have the potential to detect transiting hot Neptunes and hot Earths around low-mass stars.

From a subset of existing transit surveys with well-defined selection criteria and quantified detection efficiencies, van Saders & Gaudi (2011) combined their null results to derive upper limits on the planet fractions, viz. 5.5–1.4% for  $1.0 - 1.5R_J$  planets with  $P = 3 - 5$  d, and 1.4–0.31% for those with  $P = 1 - 3$  d. Comparing their results to those from radial velocity and transit surveys, they concluded that there is no evidence that open clusters support a fundamentally different planet population from field stars.

**Open clusters observed with Kepler** Four open clusters, all with solar or higher metallicity, lie within the original Kepler field: NGC 6866, NGC 6811, NGC 6819 and NGC 6791, in increasing order of age (Meibom et al., 2011a; Janes et al., 2014).

Chatterjee et al. (2012) reported N-body simulations which suggest that most planets in Kepler-detectable orbits would not be significantly perturbed by stellar encounters in these open clusters, estimating Kepler sur-

**Unsuccessful transit searches in open clusters:** Several groups have targeted Galactic open clusters in their search for transiting planets. Unsuccessful searches (ordered by NGC identifier) include NGC 188: 87 h over 45 nights at the Whipple 1.2-m (Mochejska et al., 2008); NGC 1245: 19 nights at the Hiltner 2.4-m (Burke et al., 2004, 2006; Pepper & Burke, 2006); NGC 2099 (M37): 20 nights at the MMT 6.5-m (Hartman et al., 2008a,b, 2009b); NGC 2158: 20 nights at the Whipple 1.2-m (Mochejska et al., 2004, 2006); NGC 2301: 14 nights at the Univ. Hawaii 2.2-m (Tonry et al., 2005; Howell et al., 2005); NGC 2660 and 6208 (von Braun et al., 2005); NGC 6633: at the 0.5-m UNSW APT (Hidas et al., 2005); NGC 6791: 8 nights at the NOT 2.5-m (Bruntt et al., 2003), 10 nights at the CFHT 3.6-m and others (Montalto et al., 2007), and 300 h over 84 nights at the Whipple 1.2-m (Mochejska et al., 2002, 2005); NGC 6819: 38 000 stars at the INT 2.5-m (Street et al., 2003); NGC 6940: 50 000 stars over 18 nights at the INT 2.5-m (Hood et al., 2005); NGC 7086: 1000 stars over 12 nights at the DAO 1.8-m (Rosvick & Robb, 2006); NGC 7789: 30 nights monitoring 33 000 stars at 900 epochs at the INT 2.5-m (Bramich et al., 2005; Bramich & Horne, 2006); the Monitor programme of ten star-forming regions and open clusters with ages 1–200 Myr which started in 2004 using various 2–4-m telescopes (Hodgkin et al., 2006; Aigrain et al., 2007; Miller et al., 2008); and the young associations IC 2391,  $\eta$  Cha, and Upper Sco (Oelkers et al., 2016).

vey yield rates of between 1–20 transiting planets for the supersolar metallicity NGC 6791, assuming that planets formed at the same frequency as observed in the field.

The first open cluster transit detections with Kepler came with Kepler–66 and Kepler–67 in the open cluster NGC 6811, their existence establishing that planets can form and survive in dense clusters (Meibom et al., 2013).

**Open clusters observed with K2** With the start of the K2 mission, specific campaigns have targeted other relevant sky-regions (see Table 6.11). Observations of the Hyades open cluster resulted in the discovery of the first Hyades transiting planet, K2–25 (Mann et al., 2016a; Douglas et al., 2016), and the 3-planet K2–136 (Ciardi et al., 2018; Mann et al., 2018). Searches in Praesepe (M44) led to the discovery of K2–95, and K2–100 to K2–104 (Libralato et al., 2016b; Obermeier et al., 2016a; Mann et al., 2017b; Pepper et al., 2017a). Searches in Upper Sco yielded K2–33 (David et al., 2016).

In the Pleiades (Campaign 4) field, K2–77 is considered an interloper, and no other cluster planets were found (Gaidos et al., 2017b). Other searches have been carried out in M67 (NGC 2682; Nardiello et al., 2016b,a), and M35 and NGC 2158 (Libralato et al., 2016a). A uniform pipeline analysis for four K2-observed open clusters is given by Rizzuto et al. (2017).

**Globular clusters** The central core of 47 Tuc was observed for 8-d by HST, yielding no candidates (Gilliland et al., 2000). Surveys of the outer regions of two clusters have been made with the ANU 1-m telescope: for 47 Tuc (22 000 stars over 33 nights; Weldrake et al. 2005)

and for  $\omega$  Cen (31 000 stars over 25 nights; Weldrake et al. 2008b). Based on known planet frequencies, more than 20 were expected in the combined (core and halo) surveys of 47 Tuc, with around five expected for  $\omega$  Cen.

Other unsuccessful globular cluster transit surveys have been undertaken for NGC 6397 imaged by HST–ACS over 126 orbits, and resulting in 5078 light curves, including 2215 cluster M0–M9 dwarfs (Nascimbeni et al., 2012); and M71 observed with the  $11 \times 11$  arcmin<sup>2</sup> field of the Near-Infrared Transiting ExoplanetS telescope (NITES), and reaching lower amplitude ( $\leq 0.02$  mag) and longer period ( $P > 2$  d) variability than previous observations, targeting some 1000 main sequence stars with sufficient photometric accuracy to detect a transiting hot Jupiter (McCormac et al., 2014).

**Why no globular cluster transits?** The absence of transits in the globular cluster 47 Tuc has been attributed to various effects. On the hypothesis that planet formation has a significant dependency on metallicity, low metallicities may contribute (Fischer & Valenti, 2005; Soker & Hershenhorn, 2007). Planetary systems may have been disrupted through the dynamical effects of high stellar densities (Davies & Sigurdsson, 2001; Bonnell et al., 2001; Armitage, 2000). Ablation by intense extreme-ultraviolet fields from massive O stars early in their lifetimes has also been suggested (Armitage, 2000).

Detailed simulations for 47 Tuc have however shown that planets in the dense core region with  $a = 1$  au would survive disruptions by stellar encounters for  $10^8$  yr, and significantly longer for the short-period planets to which transit surveys are most sensitive (Davies & Sigurdsson, 2001). In the outer regions, planets with  $a = 10$  au should still be intact, with those at 0.04 au unaffected by the cluster dynamics (Bonnell et al., 2001). Furthermore, surveys of less dense open clusters have also been largely unsuccessful, even those which are younger and more metal rich (e.g. Hartman et al., 2009b).

Another hypothesis for the paucity of cluster planets, and in particular hot Jupiters, involves the destructive effects of tides (Gu et al., 2003b; Spurzem et al., 2009). In the models of Debes & Jackson (2010) encounters between stars in dense clusters excite the orbital eccentricities. These raise tides on the star which, in turn, remove orbital angular momentum from the planet and causes it to spiral inward over Gyr time scales or less (Jackson et al., 2009). With resulting lifetimes shorter than a few Gyr, older star clusters would have fewer hot Jupiters than corresponding field stars.

A reassessment of the HST results in the light of subsequent Kepler statistics, on the hypothesis of identical planet populations, leads to expected numbers revised down to  $2.2^{+1.6}_{-1.1}$  for the relevant mass range, and therefore a null result of less significance (Masuda & Winn, 2017).

### 6.3.3 Circumbinary planets

One early approach to selecting stars with an increased prospect of having transiting planets was to observe eclipsing binary systems, whose geometry implies  $i \sim 90^\circ$ , under the assumption that the planetary and binary orbital planes are co-aligned (Doyle, 1988; Schneider & Chevreton, 1990; Hale, 1994; Schneider & Doyle, 1995; Doyle et al., 1998; Deeg et al., 2008). Configurations

in which a planet orbits one component of a widely-separated binary (in which case transits are improbable due to the arbitrary long planetary period), or is in orbit around a close binary, both result in large domains of dynamical stability (Harrington, 1977; Heppenheimer, 1978; Benest, 1998).

Observations of the short-period eclipsing binary, CM Dra with a period of 1.28 d, was pursued by the TEP (Transits of Extrasolar Planets) network since 1994, using six telescopes located around the world (Doyle et al., 1996; Deeg et al., 1998; Doyle et al., 2000). Timing of the binary eclipse minima provided a planet detection sensitivity down to about  $1 M_J$  (Deeg et al., 2000).

The commonly used ‘box least squares’ algorithm (Kovács et al., 2002) is a three-dimensional search algorithm which assumes the periodicity, and the uniformity of the transit depth, of a transiting planet. Neither of these assumptions apply in the case of circumbinary planets. Ofir (2008) developed a generalisation of the method to include an underlying binary model (around which the planet orbits), determining for each data point whether the planet was transiting the primary or the secondary, and assessing the transit depth accordingly. Blind testing applied to the CoRoT data is described by Ofir et al. (2009).

Transiting planet parameters, as well as the theories of planetary formation, depend on whether the host star is single or a binary. Daemgen et al. (2009) carried out a survey of 14 transiting planet host stars using ‘lucky imaging’ to minimise effects of atmospheric seeing. They confirmed WASP-2 as a binary, and discovered previously unknown binarity for TrES-2 and TrES-4.

### 6.3.4 Specific spectral types

**M dwarfs** The specific interest of transit surveys focused on M dwarfs (along with those of L spectral type, collectively also referred to as ultracool dwarfs) is that, because of their small radii, signals from an Earth-size (rocky) planet should be readily distinguishable, although their intrinsic variability may be a limiting factor (Caballero & Rebolo, 2002; Caballero et al., 2003; Gould et al., 2003c; Snellen, 2005; Nutzman & Charbonneau, 2008; Plavchan et al., 2008b). For the nearest ( $d < 25 - 30$  pc), relatively bright ( $J < 9 - 10$ ) M dwarfs, for example,  $\Delta m \gtrsim 0.005$  mag for planets with  $2 \leq R_p \leq 4 R_\oplus$  (Charbonneau et al., 2009).

Additionally, their habitable zone lies much closer to the host star, thus improving their geometric transit probability: for an M5 star, a planet receiving the same stellar flux as the Earth would lie only 0.074 au from the star, presenting a 1.6% geometric transit probability. Such planets may spend billions of years in the habitable zone (Andreeshchev & Scalzo, 2004; Tarter et al., 2007).

Although more than 2000 ultracool dwarfs are known, many from the 2MASS survey, their relatively

low surface density on the sky requires observing them individually. Nutzman & Charbonneau (2008) established design requirements for a network of ten 0.3-m survey telescopes. The MEarth project implemented eight identical 0.4-m telescopes in a single enclosure at Mt Hopkins, and resulted in the first such transiting planet, of  $6.5 M_\oplus$  around the 13 pc distant M dwarf GJ 1214 (Charbonneau et al., 2009, see also §6.4.3).

Blake et al. (2008) carried out a study for transit detection in the near infrared, based on 13 ultracool dwarfs observed with the 1.3-m automatic Peters telescope at Mt Hopkins, aiming at  $\sim 0.01$  mag photometry.

The 2MASS calibration fields, which were observed between 562–3692 times during the four years of the Two-Micron All Sky Survey project, have been searched for transiting M dwarfs (Plavchan et al., 2008b). From 7554 sources in the range  $K_s = 5.6 - 16.1$  mag, three M dwarf eclipsing systems have been reported, including two transiting planet candidates.

Planets accompanying M dwarfs are also known from radial velocity surveys (§2.8.4), as well as microlensing surveys (§5.10.2), and their interest also extends to other observational techniques. At intermediate separations ( $\approx 1 - 4$  au) high-precision astrometry is sensitive to planets in the mass range between Neptune and Jupiter (Casertano et al., 2008; Sozzetti et al., 2014; Perryman et al., 2014a), while the favourable planet–star contrast ratios allows for improved detectability at wide separations ( $> 5 - 10$  au) with direct imaging techniques (e.g. Bowler et al., 2012a). Atmospheric characterisation of transiting close-in super-Earths is also within reach via occultation spectroscopy (e.g. Tessenyi et al., 2012).

**Brown dwarfs** Although a number of brown dwarfs are now known to be orbited by ‘planets’ (§9.8.3), none have been discovered from transit surveys, and no dedicated brown dwarf transit surveys have been reported. An unsuccessful search of 44 nearby brown dwarfs, from Spitzer archival data, was reported by He et al. (2017b).

**Giant stars** Planets have been detected from Doppler surveys around evolved stars with  $R_\star \gtrsim 2.5 R_\odot$ , but none have been detected and further characterised from transit surveys because of their small transit depths ( $\Delta F \approx 10^{-4}$ ) and long transit durations  $t_T \gtrsim 50$  h. Assef et al. (2009) proposed to improve detection prospects using narrow-band measurements to isolate the thin ring of chromospheric emission at the limb of the giant stars.

**White dwarfs** White dwarfs are an attractive transit-search target because their small  $R_\star$  allows detection of much smaller objects for a given transit depth. Thus a rocky planet could fully occult the star, moon-sized objects would yield 10% transit depths, and even large asteroids may be detectable (Drake et al., 2010; Di Stefano et al., 2010; Agol, 2011; Faedi et al., 2011b; Law et al., 2015; Sandhaus et al., 2016).

There is now considerable evidence that white dwarfs are often surrounded by debris disks, with photospheric ‘pollution’ suggestive of accretion. Transiting planets would provide insights into planetary properties in these extreme environments, along with evolutionary constraints during the red giant phase (§8.9).

Conspiring against detection, white dwarfs are faint, while their small radii both (greatly) reduce the geometric transit probability, and also reduce the transit durations to minutes, thus demanding very high cadence. Search results are described in Section 6.14.24.

**Pulsating sdB stars** Planets that orbit their parent star at  $\leq 1$  au are expected to be engulfed when the star becomes a red giant (§8.9.1). Radial velocity observations have revealed the existence of post-red-giant stars with giant planets orbiting as close as 0.1 au or with brown dwarf companions in tight orbits, showing that these bodies can survive engulfment. What has remained less clear is whether planets can be dragged deeper into the red-giant envelope without being disrupted.

During its primary mission, Kepler observed 19 subdwarf-B (sdB) pulsators, and (candidate) planets have been found around two: Kepler-70 and Kepler-429.

**Kepler-70** Charpinet et al. (2011) reported two transiting Earth-mass bodies ( $0.4M_{\oplus}$  and  $0.7M_{\oplus}$ ) orbiting the post-red-giant, hot B subdwarf (sdB pulsator) at  $a = 0.006$  and  $0.008$  au ( $P = 5.76$  h and  $8.23$  h). These ‘planets’ probably survived deep immersion in the red-giant envelope, and may be the surviving dense cores of evaporated giant planets transported closer to the star during engulfment, which perhaps triggered the mass loss leading to the formation of the hot B subdwarf (Charpinet et al., 2011; Bear & Soker, 2012).

**Kepler-429** In addition to tens of g-mode pulsation frequencies, the Fourier spectrum of Kepler-429 shows three weak peaks at very low frequencies, interpreted as orbital modulation of three Earth-size planets in very tight orbits ( $P_1 = 5.273$ ,  $P_2 = 7.807$ ,  $P_3 = 19.48$  h), and illuminated by stellar radiation (Silvotti et al., 2014). The period ratios  $P_2/P_1 = 1.481$  and  $P_3/P_2 = 2.495$  are very close to the 3:2 and 5:2 resonances, respectively. One of the main pulsation modes at  $210.68 \mu\text{Hz}$  corresponds to the third harmonic of the inner planet’s orbital period, suggesting that the g-mode pulsations are tidally excited.

### 6.3.5 Solar system transit observations

**Earth as a transiting planet** An observer on the Moon during a lunar eclipse would experience a transit of the Earth in front of the Sun (Vidal-Madjar et al., 2010). Arnold et al. (2014) made simultaneous observations with the ESO-HARPS and UVES spectrographs of the 2010 December 21 lunar eclipse, with high-resolution umbra and penumbra spectra from 310–1040 nm. From their detection of the  $\text{O}_2$  A-band,  $\text{O}_3$ ,  $\text{H}_2\text{O}$  and Na, and the spectral signature of Rayleigh scattering, they argue that these signatures will be within reach of the E-ELT in 8 h of integration for an Earth twin at 10 pc.

García Muñoz et al. (2012) used observation of the lunar eclipse of 2008 August to argue that (and by analogy for similar exoplanet systems) refraction prevents access to the lower (12–14 km) atmosphere, and hence the bulk of the spectroscopically active atmospheric gases, and that the effective optical radius of the Earth in transit is modulated by refraction, varying by  $\sim 12$  km from mid-transit to internal contact. Atmospheric  $\text{O}_3$  has a particularly strong effect on the colour of the entire sky when the Sun is near or just below the horizon (Fosbury et al., 2011, see also Section 6.14.11).

A comparison of atmospheric models and Earth’s transmission spectrum, made during the lunar eclipse of 2011 December, identified a number of relevant features, including the prominent Chappuis  $\text{O}_3$  band (400–650 nm, contributing to the deep blue colour of the sky at dusk), resolution of individual  $\text{O}_2$  lines and isotopes, and a Raman (inelastic) scattered component in addition to Rayleigh (elastic) scattering (Yan et al., 2015a). Signatures were also detected in the associated Rossiter-McLaughlin effect (Yan et al., 2015c).

The EPOXI mission made several observations of the Earth as a transiting planet (§6.10.1). Messenger mission brightness curves of Earth have been used to synthesise its polarisation signature (García Muñoz, 2015). Use of the Earth’s atmosphere as a proxy for transmission spectroscopy of exo-Earths has been detailed by, e.g. Bétrémieux & Kaltenegger (2013, and references).

More generally, sunlight scattered by Earth illuminating the side of the Moon facing away from the Sun (earthshine) is used as an exoplanet analogue of Earth’s atmosphere (box, page 641).

**Venus as a transiting planet** The 2004 June 8 transit of Venus was observed in transmission spectroscopy using TRACE (Pasachoff et al., 2011), and also the VTT (Vacuum Tower Telescope) in Tenerife (Hedelt et al., 2011). The latter identified  $\text{CO}_2$  absorption lines in the upper atmosphere, relative abundances of the three most abundant  $\text{CO}_2$  lines, and resolved the planet’s limb, showing Doppler-shifted absorption lines probably caused by high-altitude winds. It was also observed from space by the Solar Dynamics Observatory (SDO). Other modeling is described by Chiavassa et al. (2015). The 2012 June 5 transit of Venus was considered in the context of its atmospheric effects on transit curves (García Muñoz & Mills, 2012), and observed in reflected light from the Moon as a way of calibrating exoplanet atmospheres (Hedelt et al., 2011; Ehrenreich et al., 2012b).

**Jupiter as a transiting planet** Montañés-Rodríguez et al. (2015) obtained the transmission spectrum of Jupiter, from ultraviolet to near infrared, by observing its satellite Ganymede while passing through Jupiter’s shadow, i.e., during a solar eclipse from Ganymede. The spectrum shows strong extinction due to clouds and hazes in the atmosphere, strong  $\text{CH}_4$  absorption, atomic

transitions of Na, and a spectral signature attribute to a (Jupiter) stratospheric layer of crystalline H<sub>2</sub>O-ice.

Using resolved images of the Sun from NASA's Solar Dynamics Observatory spanning 3.5 yr of Solar Cycle 24, Llama & Shkolnik (2015) simulated transit light curves of a hot Jupiter to investigate the impact of solar-like activity on atmospheric parameters in the X-ray to optical, and on the determination of  $R_p/R_*$ . Llama & Shkolnik (2016) made a similar analysis for disk-integrated images in Ly- $\alpha$ , using them for a comparison with transit observations of 55 Cnc, GJ 436, and HD 189733.

**Saturn as a transiting planet** Dalba et al. (2015) used solar occultation spectroscopy from Cassini-VIMS to extract the 15  $\mu$ m transmission spectrum of Saturn. They detected absorption from CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>2</sub>H<sub>2</sub>, aliphatic (non-aromatic) hydrocarbons, and possibly CO, at up to 90 ppm, despite the presence of NH<sub>3</sub> clouds. Atmosphere models failed to reproduce a large absorption feature near 3.4  $\mu$ m, attributed to C<sub>2</sub>H<sub>6</sub> and a C-H stretching mode of an unknown hydrocarbon. Atmospheric refraction (§6.14.11), as opposed to clouds or haze, determined the minimum altitude that could be probed during transit.

**Other** The possibility of observing *simultaneous* transits of solar system planets from particularly favourable locations is noted in Section 6.14.16.

The concept of the Earth's transit zone has some relevance in discussions of SETI strategies which might exploit communicating with civilisations which know of Earth's habitability as a result its specific atmospheric transit signatures (§11.8.6).

## 6.4 Surveys from the ground

Two ground-based surveys, HAT and WASP, have been responsible for the majority of transiting planets discovered from the ground, and they are described here in some detail. Other ground-based surveys, past, present, or future, are summarised in the following sections, the division being according to whether (or not) the programmes have so far detected transiting planets.

Transiting planet observations and discoveries from the ground have greatly benefited from the development of automated telescopes and networks. A review of their development and application, to exoplanet studies and elsewhere, is given by Bakos et al. (2013).

### 6.4.1 HAT/HATNet

The HATNet project (Bakos, 2018) comprises HAT-North which started observations in the northern hemisphere in 2003, HAT-South which began in the southern hemisphere in 2009, and the second-generation HATPI, which should be operational in 2018 (§6.4.4).

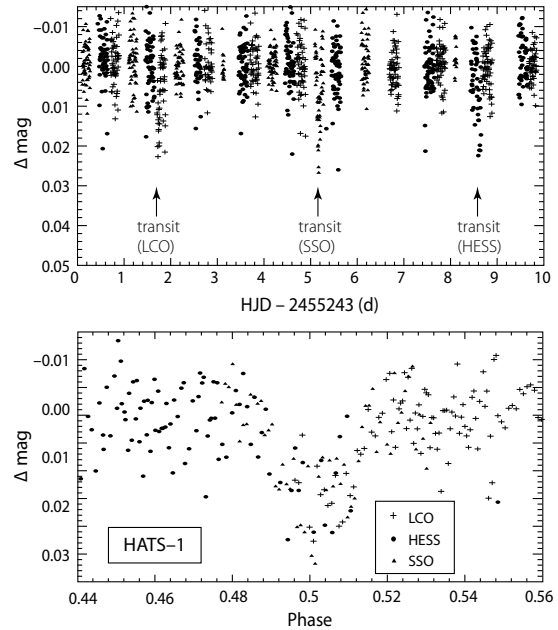


Figure 6.4: HATS-1, showing a 10 d period (from 2010 February 15) from the HAT-South discovery light curve containing 1351 out of 12 000 observations. Top: magnitude deviation (from the median) versus time, with different symbols denoting different sites (see legend). Over this period, a comparable fraction of observations come from each of the three HAT-South sites, and transits are detected by each at a similar significance. Bottom: phase-folded light curve centred on the transit. From Penev et al. (2013, Figure 5), by permission of IOP Publishing/AAS.

**HAT-North** The Hungarian Automated Telescope project started in 2003 with a single telescope (Bakos et al., 2011b). HAT-North subsequently developed into a network of six identical automated northern hemisphere telescopes, four at the SAO Fred Whipple Observatory (Arizona), and two at the SAO Submillimeter Array site, Mauna Kea (Bakos et al., 2002, 2004). Each consists of a 0.11-m aperture  $f/1.8$  lens and a  $4k \times 4k$  CCD with 9 arcsec pixels, providing a  $10.6^\circ \times 10.6^\circ$  field, with a precision at 3.5-min cadence of 4 mmag at  $r \sim 9.5$ , and 10 mmag at  $r \sim 12.1$  (Bakos et al., 2011b). The original HATNet used  $2k \times 2k$  front illuminated CCDs with Cousins  $I$ -band filters, but was replaced by  $4k \times 4k$  CCDs and Cousins  $R$  filters in 2007 September. The filter was changed to Sloan  $r$  in 2008 July.

**HAT-South** Since late 2009, six telescopes at three southern sites widely distributed in longitude (Las Campanas, Chile; Siding Spring, Australia; HESS  $\gamma$ -ray site, Namibia) have been jointly operational as HAT-South (Bakos et al., 2009a, 2013). Each houses four 0.18-m diameter  $f/2.8$  telescope tubes on a common mount, imaged using four  $4k \times 4k$  CCD cameras and Sloan  $r$  filters, with a pixel scale of 3.7 arcsec, resulting in an  $8.2^\circ \times 8.2^\circ$  field. HAT-South can continuously monitor 128 sq. deg.

**Individual HAT (and HATS) objects of note:**

**HAT-P-1** the planet orbits one component of a stellar binary (Bakos et al., 2007b). Secondary eclipses have been measured with Spitzer (Todorov et al., 2010a), and from the ground at 4 $\sigma$  with WHT (de Mooij et al., 2011). Eclipse observations with HST have detected both H<sub>2</sub>O (Wakeford et al., 2013) and Na absorption (Nikolov et al., 2014).

**HAT-P-2** the first massive (9M<sub>J</sub>) transiting planet, and with the highest eccentricity,  $e = 0.52$  (Bakos et al., 2007a).

**HAT-P-6** an early HATNet discovery (Noyes et al., 2008), with the Rossiter–McLaughlin effect revealing a retrograde orbit (Hébrard et al., 2011a).

**HAT-P-7** the first (probably) retrograde orbiting planet (Narita et al., 2009b; Winn et al., 2009d; Benomar et al., 2014), perhaps with an accompanying third body (Winn et al., 2009d; Narita et al., 2010b). It has been the subject of extensive asteroseismology analysis (Christensen-Dalsgaard et al., 2010; Oshagh et al., 2013c; Lund et al., 2014). It was discovered in the pre-operational Kepler field, and further transits were subsequently observed by Kepler (Borucki et al., 2009; Morris et al., 2013; Esteves et al., 2013; Van Eylen et al., 2013), including detection of tidally-distorted ellipsoidal light curve variations (Welsh et al., 2010; Jackson et al., 2012b), and planet-induced stellar gravity darkening (Morris et al., 2013).

**HAT-P-11** one of the first transiting Neptunes, in a misaligned orbit (Bakos et al., 2010). Star spots have provided insight into the stellar rotation and orbital alignment (Sanchis-Ojeda & Winn, 2011; Béky et al., 2014a). There are suggestions of radio emission at 150 MHz (Lecavelier des Etangs et al., 2013), perhaps attributable to lightning (Hodosán et al., 2016b). It is one of a number of systems in which the host star rotates with a period equal to an integer multiple of the orbital period of their close-orbiting planet, in this case with a period ratio of 6:1 (Béky et al., 2014a).

**HAT-P-12** the first inflated Saturn. At the time of its discovery, HAT-P-12 b was the least massive H/He-dominated gas giant planet known, a record previously held by Saturn (Hartman et al., 2009a).

**HAT-P-13** is a system comprising an inner transiting planet and an outer non-transiting planet, and the first transiting system known to be multiple. HAT-P-13 b is a classical hot Jupiter on a circular orbit ( $M = 0.85M_J$ ,  $R = 1.28R_J$ ,  $e = 0.01$ ,  $P = 2.9$  d) transiting a G4V star. HAT-P-13 c is an outer, massive high eccentricity companion ( $M \sin i \sim 15M_J$ ,  $P = 428$  d,  $e = 0.67$ ) detected from radial velocity measurements (Bakos et al., 2009b). A third planet has been suspected from radial velocity trends, and transit time studies, with Pál et al. (2011) reporting discontinuities in the transit time ephemeris, perhaps attributable to a long-period eccentric perturber near pericentre.

**HAT-P-14** with a planet with a near-grazing transit (Torres et al., 2010b), and in a retrograde orbit (Winn et al., 2011b).

**HAT-P-17** a 2-planet system, with an inner transiting planet in a short-period (10 d) eccentric ( $e = 0.34$ ) orbit, and an outer (6000 d) non-transiting planet discovered from radial velocity measurements (Howard et al., 2012a).

**HAT-P-27** discovered both by HAT (Béky et al., 2011), and as WASP-40 with a near-grazing transit (Anderson et al., 2011a).

**HATS-1** first of the HAT-South planets (Penev et al., 2013). It typifies the properties of ground-based discoveries, with  $P = 3.446$  d (close to the mode),  $M_p = 1.86M_J$  (slightly higher than typical),  $R_p = 1.30R_J$  (close to the median for its mass), around a star that is an almost exact solar analogue (see Figure 6.4).

close to the anti-solar direction to  $R \approx 14$ . Photometric precision reaches  $\sim 6$  mmag at 4-min cadence for the brightest non-saturated stars at  $r \sim 10.5$ .

Its complete longitudinal coverage permits a near-continuous monitoring of selected fields (Figure 6.4). At the same time, the larger aperture, slower focal ratio, and lower sky background, allows fainter stars to be monitored (with reduced crowding), increasing the number of dwarf stars observed at 1% photometry over a year by a factor of 3, and increasing the yield of smaller planets.

**Designation** Host stars are designated HAT-P-*nnn* for discoveries from HAT, and HATS-*nnn* from HAT-South.

**Data processing** Discovery and confirmation employs the following steps (Latham et al., 2009; Bakos et al., 2010): (1) candidate identification; (2) high-resolution, low-S/N ‘reconnaissance’ spectra to efficiently reject many false-positives; (3) higher-precision photometric transit observations to refine parameters and derived a stellar density; and (4) high-resolution, high-S/N ‘confirmation’ spectroscopy to determine the stellar orbit, characterise the host star, and exclude blends.

The HAT-South data reduction, from raw pixel images to trend-filtered light curves and transiting planet candidates, is described by Bakos et al. (2013).

**General properties** By the end of 2017, 91 HAT planets had been reported (88 transiting), 60 from HAT-North (of which 3 were radial velocity discoveries in existing HAT systems), and 31 from HAT-South.

HAT planets span a diversity of systems, architectures, and physical properties. Masses range from that of Neptune,  $\sim 0.06M_J$  (HAT-P-11, HAT-P-26) to  $9M_J$  (HAT-P-21). Sizes range from compact,  $\sim 0.4R_J$  (HAT-P-11) to highly inflated,  $\sim 1.9R_J$  (HAT-P-65). Periods range from 1.2 d (HAT-P-23) to transiting planets with  $P \sim 16$  d (HATS-17), with eccentricities reaching  $e \sim 0.5$  (HAT-P-2), and  $e \sim 0.67$  for the non-transiting HAT-P-13 c. There are just three 2-planet systems, where the outer planets have been discovered by radial velocity measurements (HAT-P-13, HAT-P-17, and HAT-P-44).

**Individual objects** Some specific HAT systems of note are given in the box on page 163, and a bibliography of all discoveries is given in Appendix D.

### 6.4.2 WASP/SuperWASP

The WASP consortium (Wide-Angle Search for Planets) employs two wide-field camera arrays in the north (La Palma) and south (Sutherland, S. Africa) hemispheres (Pollacco et al., 2006; Collier Cameron et al., 2009b; Wheatley, 2015). The prototype WASP0 monitored 35 000 stars in Draco for two months (Kane et al., 2004, 2005a; Christian et al., 2006), with interruptions to view a field in Pegasus when transits of HD 209458 occurred (Kane et al., 2005b).

Each SuperWASP 0.11-m aperture telescope incorporates eight 2k×2k CCD cameras on a robotic equatorial mount, forming a mosaic with a field of view of  $15^\circ \times 30^\circ$  (RA, dec), and a pixel size of 14 arcsec. During the first two years of full operations, starting in 2006 May, search fields have been primarily located at  $\delta \approx \pm 30^\circ$ . Fields are observed if accessible for at least 4 h each night, and the observing season for a given object typically spans 120–150 nights.

Data rates are up to 100 Gbyte per night. Details of the data processing are given by, e.g., Pollacco et al. (2006); Collier Cameron et al. (2009b). Public release details are described by Butters et al. (2010).

SuperWasp reports a success rate of one confirmed planet per five or six selected for radial velocity follow-up (typically using SOPHIE at the 1.9-m OHP telescope, and CORALIE at the 1.2-m Euler telescope, La Silla).

**Designation** Initial targets are assigned a candidate identifier of the form 1SWASPnnn, with WASP–nnn identifiers assigned after confirmation as a planet.

**Results** The first 6 months of SuperWASP–north produced light curves of 6.7 million objects with 12.9 billion data points (Christian et al., 2006; Clarkson et al., 2007; Lister et al., 2007; Street et al., 2007; Kane et al., 2008). Long-term rms scatter for non-variable stars, after pipeline treatment, is 4 mmag at  $V = 9.5$ , degrading to 10 mmag at  $V = 12$ .

As of December 2010, SuperWASP had discovered about 30 transiting planets since its inaugural observing season in 2004, roughly half in each hemisphere. By 2013, SuperWASP had surveyed most of the sky, and had observed more than 30 million stars between 8.5–13.5 mag (Triaud et al., 2013a; Smith et al., 2014b).

By the end of 2017, WASP discoveries numbered around 130 (130 transiting, and a further four in multi-planet systems discovered by follow-up radial velocity observations). They comprise a rich diversity of systems. Example light curves are shown for WASP–3 (Figure 6.5), WASP–12 (Figure 6.6), and WASP–17 (Figure 6.7).

Many thousands of other variables have been discovered and characterised in the WASP data, including eclipsing binaries (e.g. Norton et al., 2011; Lohr et al., 2012; Smalley et al., 2014; Lohr et al., 2015), and RR Lyrae variables (Greer et al., 2017).

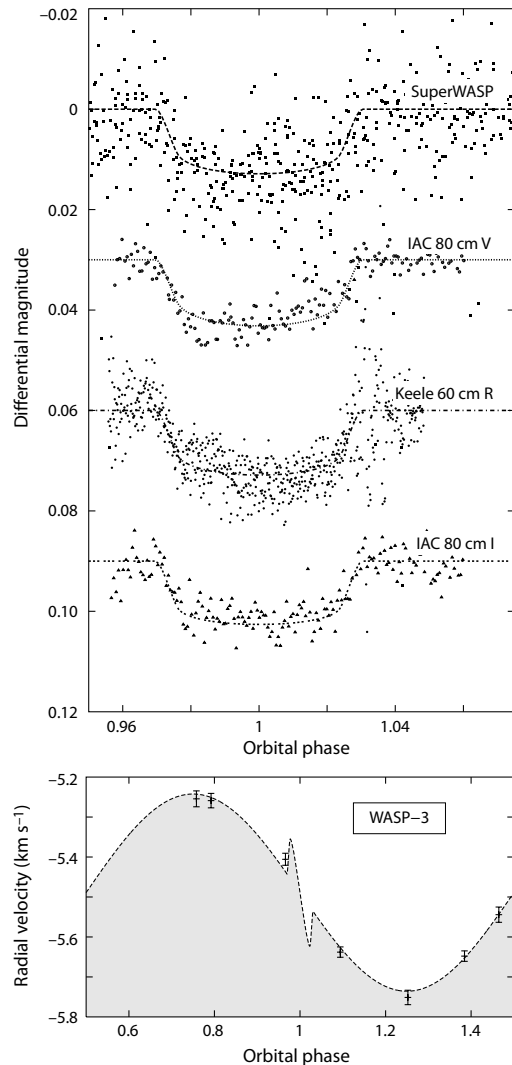


Figure 6.5: WASP–3: simultaneous solution to SuperWASP–N, IAC 80 V I and Keele R photometry. Lower panel: fit to the radial velocity data, including the predicted Rossiter–McLaughlin effect (§6.18) for the star’s  $v \sin i = 13.4 \text{ km s}^{-1}$ . From Pollacco et al. (2008, Figure 3), © Oxford University Press.

**General properties** More than 10 of the WASP host stars have  $V < 10$  mag (with WASP–18 and WASP–33 amongst the brightest), making them particularly suitable for a variety of follow-up studies (including measurement of the Rossiter–McLaughlin effect, and transmission spectroscopy). A similar number are relatively nearby,  $d < 100$  pc, with WASP–69, WASP–80, and WASP–29 amongst the nearest, at about 50–70 pc.

Orbital periods range from very short, with a few with  $P < 1$  d, and as low as 0.8 d for WASP–19 and WASP–47. The longest periods of the WASP transiting planets are  $P \sim 10$ –11 d in the case of WASP–117 and WASP–130.

Densities range from very low (for a subset of the



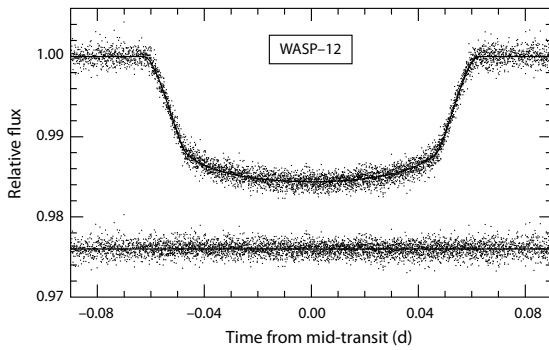


Figure 6.6: An example of high-quality ground-based transit measurements for WASP-12 b. The transit light curve combines 19 high-quality phase-folded observations, and the best-fit model is shown as the solid line. From Maciejewski et al. (2013a, Figure 4), reproduced with permission © ESO.

hot inflated planets) of  $0.12 \text{ Mg m}^{-3}$  ( $\sim 0.1\rho_{\text{J}}$ ) for WASP-17 and WASP-94A, to the much higher densities ( $7\text{--}8 \text{ Mg m}^{-3}$ , presumably with a high metal fraction) of WASP-18 and WASP-89.

There are four multi-planet systems: WASP-53 is a 2-planet system which both transit; WASP-8 and WASP-41 are 2-planet systems with the second discovered from radial velocities; while WASP-47 ( $d \sim 200 \text{ pc}$ ,  $V = 11.9$ ) is a 4-planet system of which three transit.

Discovery from ground imposes a lower mass limit of  $\sim 0.2M_{\text{J}}$ , although the 4-planet system WASP-47, discovered through the transiting  $1.1M_{\text{J}}$  planet b, also possesses two of significantly lower mass, including WASP-47 d at  $0.05M_{\text{J}}$ .

The Rossiter–McLaughlin effect has been measured for more than 50 WASP systems (§6.18.7 and Table 6.2). The best precision attained is  $\lambda = -112.93^{+0.23}_{-0.22}$  deg for WASP-33 (Johnson et al., 2015a). Around a third of these systems are highly misaligned, with some of the largest values of  $\lambda = -153^\circ$  for WASP-2,  $\lambda = -148^\circ$  for WASP-17, and  $\lambda = -140^\circ$  for WASP-15 (Triaud et al., 2010).

Secondary eclipses have been measured in about 20 WASP systems, with associated atmospheric constraints from ground-based telescopes and Spitzer. A few have been measured in all of J, H, and K, including WASP-5 (Chen et al., 2014b), WASP-12 (Croll et al., 2011b), and WASP-46 (Chen et al., 2014d).

**Individual objects** Some specific WASP systems of note are given in the box on page 166, and a bibliography of all discoveries is given in Appendix D.

### 6.4.3 Other searches reporting detected planets

This section summarises other surveys that have detected planets to date. It therefore includes ongoing surveys as well as some no longer operational.

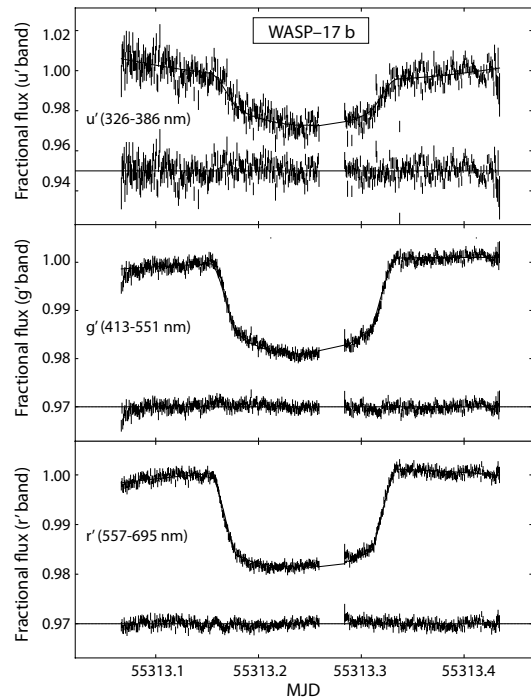


Figure 6.7: WASP-17 ( $V=11.6 \text{ mag}$ ,  $P=3.74 \text{ d}$ ) observed with ULTRACAM at the 3.5-m NTT on 2010 April 26. The instrument observes simultaneously in three bands. Observations were acquired at 7.8-s integration in g and r, and at 31-s in u, binned here (solid crosses with  $1\sigma$  standard errors) at 311 s in g and r, and 623 s in u. Data gaps are due to pointing constraints. Best fitting models and residuals are shown for each band. From Bento et al. (2014, Figure 2), © Oxford University Press.

**KELT** The Kilodegree Extremely Little Telescope (KELT) is a joint project of The Ohio State University, Vanderbilt University, and Lehigh University. It consists of two small-aperture, wide-field, robotic telescopes which have been monitoring  $\sim 50\%$  of the northern (KELT-North in Arizona) and southern (KELT-South in S. Africa) skies since 2005 and 2009 respectively (Pepper et al., 2004, 2007, 2012; Oberst et al., 2014). Both stations are continuing to operate, and monitoring around 250 000 stars. To the end of 2017, 18 planets have been reported, all with  $V < 12 \text{ mag}$ , including five of the 25 brightest known transiting planet host stars.

**Lupus (Siding Spring Observatory WFI)** The eight CCD Wide Field Imager (WFI) of the Siding Spring Observatory, Australia, was used for a  $52 \times 52 \text{ arcmin}^2$  transit survey towards Lupus in 2005–06 June. The survey resulted in the discovery of Lupus-TR-3 (Weldrake et al., 2008a); of their other candidates, Lupus-TR-1 and 4 are blended systems, while Lupus-TR-2 is a binary (Bayliss et al., 2009b). A deeper survey, SuperLupus, doubling the number of images of the same field from 1700 to 3400, was completed in 2008 (Bayliss et al., 2009a). Statistical results are described by Bayliss & Sackett (2011).

**Individual WASP objects of note:**

**WASP-8** is a 2-planet system, with planet b being the highest eccentricity WASP planet ( $e = 0.31$ ), moving on a retrograde orbit with respect to the rotation of its host star (Queloz et al., 2010).

**WASP-10** the host star exhibits pronounced photometric variability, attributed to rotational modulation of star spots. Periodic modulation in the transit times of WASP-10 b may indicate an additional perturbing body (Maciejewski et al., 2011c).

**WASP-12** a  $1.41M_J$  planet orbiting extremely close to a late-F/early-G star ( $M_* = 1.35M_\odot$ ), with  $P = 1.09$  d and  $a = 0.023$  au ( $a \equiv 4.94R_\odot \equiv 3.15R_*$ ). The planet is one of the most irradiated ( $T_{\text{eq}} = 2500 - 3000$  K) and highly inflated. The planet's Roche radius,  $1.85R_p$ , is only slightly larger than the  $R_p$  derived from optical transit measurements, suggesting that mass loss from the planet to the star is likely (at a rate of  $10^{-7}M_J \text{ yr}^{-1}$ ), and that the stellar wind may influence the planet atmosphere (Li et al., 2010b). Resulting effects include tidal dissipation (Li et al., 2010b), and a combination of bow shocks and Roche lobe overflow resulting in variations in transit depth and ingress/egress times (Fossati et al., 2010b; Lai et al., 2010; Llama & Shkolnik, 2015). The planet's surface is distorted by the star's gravity, and the light curve produced by its prolate shape is expected to differ by about 10% from that of a spherical planet. Dissipation of the star's tidal perturbation in the planet's convective envelope may have provided the energy source for its large volume (Li et al., 2010b).

**WASP-17** planet with a low density and inflated atmospheric scale height, in a retrograde orbit (Anderson et al., 2010b; Bayliss et al., 2010). With one of the lowest densities of all known planets,  $\rho = 0.09 \text{ Mg m}^{-3}$ , a factor 10 smaller than Jupiter, it has one of the largest atmospheric scale heights and, as such, a good target for transmission spectroscopy.

**WASP-18** massive, hot, short-period planet, with evidence for tidal decay (Hellier et al., 2009a). Transit time variations have been attributed to the stellar quadrupole moment (Watson & Marsh, 2010). Effects of tidal interaction and stellar spin-up were studied by Brown et al. (2011a), and tidal effects on radial velocity by Arras et al. (2012).

**WASP-19** very short-period ( $P = 0.79$  d) hot planet; with stellar rotation and tidal spin-up (Hebb et al., 2010). Secondary eclipses have been observed from ground with VLT-HAWK-I (Anderson et al., 2010a; Gibson et al., 2010a), NTT-ULTRACAM (Burton et al., 2012), and ASTEP 400 in the Antarctic (Abe et al., 2013c). Effects of tidal interaction and stellar spin-up were studied by Brown et al. (2011a), and tidal effects on radial velocity by Arras et al. (2012). Star spots allow measurement of the star-planet spin-orbit projection (Tregloan-Reed et al., 2013).

**WASP-21** orbiting a probable thick disk host star (Bouchy et al., 2010).

**WASP-29** a very low mass planet ( $0.24M_J$ , Hellier et al., 2010).

**WASP-33** at the time of its discovery, the brightest host star with a transiting planet ( $V = 8.14$ ,  $P = 1.2$  d), and the first gas giant discovered around a  $\delta$  Scuti star (Collier Cameron et al., 2010b). The observed stellar pulsations have been attributed to tidal excitation by the planet (Collier Cameron et al., 2010b; Herrero et al., 2011). Prospects for detecting classical and relativistic nodal precession (which exceeds that of the Sun-Mercury system by a factor  $\sim 10^{10}$ ) have been evaluated by Iorio (2011b).

**WASP-43** a very short-period ( $P = 0.81$  d) hot Jupiter orbiting cool low-mass star (Hellier et al., 2011b). Observed X-ray emission and the inferred mass loss have been derived from XMM-Newton observations (Czesla et al., 2013).

**WASP-47** a 4-planet system, with planet a transiting (Hellier et al., 2012), and planet b discovered from follow-up from radial velocity measurements (Neveu-VanMalle et al., 2016). Two further planets c and d, both transiting, and demonstrating transit time variations, were amongst the first discoveries with K2 (Becker et al., 2015).

**WASP-67** a hot Jupiter observed to undergo only partial (grazing) transits (Mancini et al., 2014b, see §6.14.14).

**WASP-80** gas giant around an M dwarf, with one of the largest transit depths known of nearly 3% (Triaud et al., 2013a).

**WASP-94** two hot-Jupiters, each orbiting one component of 15 arcsec binary, with the large mutual inclination indicating that at least one must be significantly inclined to stellar binary plane (Neveu-VanMalle et al., 2014).

**ISWASP J1407** although not attributed directly to a planet, this star shows long, deep, eclipses, modeled as a system of circumstellar or circumplanetary disks at  $r > 1.7$  au. It is described further in Section 6.14.6.

**MACHO/MOA** Transit searches have been made in the MACHO microlensing photometry database (Drake & Cook, 2004; Hügelmeier et al., 2007), and the 2000–05 MOA observations of 7 million stars (Abe et al., 2005; Fukui et al., 2009). Only MAESTRO-1 b was considered to be a possible planet (Setiawan et al., 2008c).

**MASCARA** The 'Multi-site All-Sky CAmeRA' consists of five cameras at each of two stations, La Palma and La Silla, providing nearly full-sky 24-h coverage to 8 mag at sub-minute cadence (Snellen et al., 2012, 2013b; Spronck et al., 2014a; Lesage et al., 2014; Spronck et al., 2014b; Stuik et al., 2014; Talens et al., 2017c). The La Palma station has been operational since 2015 Jan-

uary, the La Silla station since 2017 July. The 2.8% eclipse depth of HD 189733 b was detected in 5-min binning at  $5\sigma$  (Lesage et al., 2014). By the end of 2017, two discoveries (both hot Jupiters) had been reported: MASCARA-1 b, transiting a  $V = 8.3$  mag A star (Talens et al., 2017a), and MASCARA-2 b ( $\equiv$  KELT-20 b), transiting a  $V = 7.6$  mag A star (Talens et al., 2017b). A number of other candidates are in the process of follow-up as this volume goes to press (Snellen, priv. comm., April 2018).

**MEarth** The MEarth project uses eight identical 0.4-m automated telescopes (two operational since January 2008) in a single enclosure at Mt Hopkins, to monitor 2000 nearby M dwarfs with masses between 0.10 –

**Individual other transiting objects of note:** (from various transit surveys, apart from CoRoT (p.173), HAT (p.163), Kepler (p.179), WASP (p.166), and radial velocity (p.170) discoveries)

**GJ 1132** the first discovery by M<sub>Earth</sub>–South (Berta-Thompson et al., 2015).

**GJ 1214** a super-Earth at 15 pc, discovered by the M<sub>Earth</sub> project (Charbonneau et al., 2009). It is a low-mass object ( $0.02M_{\text{J}}$ ), well suited for transmission spectroscopy, and extensive studies with various ground and space facilities (see Appendix D) have studied its atmospheric composition, aiming to establish whether the atmosphere is dominated by relatively heavy molecules (such as  $\text{H}_2\text{O}$ ,  $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{CO}_2$ , or  $\text{N}_2$ ) or high-altitude clouds obscuring its lower layers. HST observations confirm a featureless spectrum, and rule out a cloud-free atmosphere (Kreidberg et al., 2014b, and references).

**OGLE-TR-56** the second transiting exoplanet discovery (after HD 209458 b), and the first found by a photometric wide-field survey (Konacki et al., 2003a). The host star is faint,  $V = 16.6$ , the transit is near-grazing, and the system has been the subject of investigations into mass loss, tidal dissipation, tidal locking, and stellar spin-up (Griessmeier et al., 2004; Pätzold et al., 2004; Erkaev et al., 2007; Carone & Pätzold, 2007; Arras et al., 2012).

**PTFO 8-8695** is a planet candidate from the Palomar Transient Factory Orion project (also known as PTF0-1 and CVSO 30), and the first transiting exoplanet candidate orbiting a pre-main-sequence star ( $M_{\star} \sim 0.34M_{\odot}$ ,  $M_{\text{p}} \sim 3M_{\text{J}}$ ,  $P = 0.45$  d). The transit profiles are of unusual shape, and differ significantly between the 2009 and 2010 observations, the latter with greater transit depth and shorter duration (van Eyken et al., 2012). Detailed modeling by Barnes et al. (2013a) invokes the effect of gravity darkening due to a rapidly rotating host star with a complex precessional motion (see §6.19.5 and Figure 6.75). A possible second planet (Schmidt et al., 2016) would give orbit periods for the suggested 2-planet system as 0.45 d and 27 000 yr, and suggests possible formation via planet–planet scattering.

**TRAPPIST-1** was discovered as a 3-planet transiting system around a faint, ultracool (M8) dwarf (2MASS J23062928-0502285) at a distance of 12 pc, based on 1.2 min cadence observations for 245 h over 62 nights from 2015 September 17 to December 28 (Gillon et al., 2016). It was later recognised as a 7-planet transiting system, all in a resonant chain (Luger et al., 2017c), with the planets all of terrestrial mass probably orbiting within their habitable zone (Gillon et al., 2017c). The system provides strong circumstantial evidence for convergent migration (Tamayo et al., 2017), as well as one in which lithopanspermia (§11.8.3) has significantly improved prospects compared to the solar system. See further bibliography in Appendix D.

**TrES-2** first planet discovered in the pre-operational Kepler field (O’Donovan et al., 2006a), with a very low albedo (Kipping & Spiegel, 2011). It has near-grazing transits, which have been used to place limits on transit time changes due to secular changes in orbit inclination (Mislis & Schmitt, 2009; Scuderi et al., 2010; Schröter et al., 2012). It is one of the early discoveries showing relativistic beaming and ellipsoidal variations, used to estimate star and planet masses (Barclay et al., 2012). Polarimetry has been carried out with OPTIMA (Słowikowska et al., 2011).

**WTS-1** the first planet found from the near-infrared UKIRT-WFCAM transit survey, a hot Jupiter with one of the largest radius anomalies ( $M_{\text{p}} = 4.0M_{\text{J}}$ ,  $R_{\text{p}} = 1.5R_{\text{J}}$ ,  $P = 3.35$  d) in its mass range (Cappetta et al., 2012).

**WTS-2** short-period orbit ( $P = 1.02$  d), at a distance 1.5 times its Roche radius (Birkby et al., 2014). The planet’s predicted remaining lifetime is just 40 Myr (assuming a tidal dissipation quality factor for the host star  $Q' = 10^6$ ), corresponding to a shift in transit arrival time of 17 s over 15 yr, and so providing potential constraints for theories describing how frictional processes within a host star affect the tidal orbital evolution of its companion giant planets.

$0.35M_{\odot}$ , selected from nearby stars with large proper motion (Nutzman & Charbonneau, 2008; Irwin et al., 2009), and targeting transits down to a few  $M_{\oplus}$  in their habitable zones. In its first four years of operation (2008–13) it has resulted in the detection of a single  $6.5M_{\oplus}$  ( $2.7R_{\oplus}$ ) transiting planet around the 13 pc distant M dwarf GJ 1214 (Charbonneau et al., 2009), a discovery rate (for  $2 - 4R_{\oplus}$  planets) estimated to be broadly consistent with that expected from the Kepler statistics (Berta et al., 2013). The M<sub>Earth</sub>–South array, operating since 2014, consists of eight 0.4-m robotic telescopes at CTIO, Chile, and observes M-dwarfs within 33 pc and  $R_{\star} < 0.35R_{\odot}$  (Berta et al., 2012b; Irwin et al., 2015).

**NGTS** The Next Generation Transit Survey is a wide-field transit survey located at Paranal, Chile. It employs twelve 0.2-m f/2.8 robotic telescopes, operating at 600–900 nm, and targets bright ( $V < 13$  mag) stars, predominantly of spectral type K and early M, with a photometric accuracy of 0.1% or 1 mmag at 13 mag (Chazelas et al., 2012b; Wheatley et al., 2013, 2014; Wheatley, 2015;

Günther et al., 2017a; McCormac et al., 2017). A collaboration between UK, Switzerland and Germany, key technologies were demonstrated using a prototype on La Palma (2009–2010), and it benefits from the hardware and software heritage of SuperWASP. First light was in 2015 January (for the first telescope unit), with full survey operations starting in 2016 April (West et al., 2016b; Wheatley et al., 2018). It employs a pipeline centroiding module for automated candidate vetting (Günther et al., 2017b). Simulations suggest that, for a 4-yr survey and limited by red noise of 1 mmag, NGTS may discover some  $150 \pm 10$  Jupiter-sized planets,  $55 \pm 8$  Saturns,  $16 \pm 4$  large Neptunes,  $19 \pm 5$  small Neptunes, and  $4 \pm 3$  super-Earths (Günther et al., 2017a).

The first discovery, NGTS-1, is a  $P = 2.674$  d,  $M_{\text{p}} = 0.8M_{\text{J}}$  planet orbiting an M dwarf, with deep (2.5%) grazing transits, and the third (and most massive) transiting giant planet around an M dwarf (Bayliss et al., 2018a). Several more have since been confirmed, and tens of candidates are in the process of follow-up as this volume goes to press (Wheatley, priv. comm., April 2018).

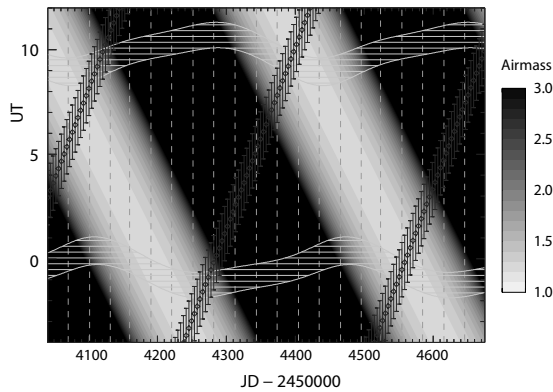


Figure 6.8: Observable transits of OGLE-TR-111 between 2006 November and 2008 August, as seen from northern Chile. Diamonds indicate transit centres; vertical ‘error bars’ indicate transit durations. Line-filled regions indicate morning and evening twilight, and dashed vertical lines indicate month boundaries. Increasing shading density indicates increasing airmass (scale at right). From Minniti et al. (2007, Figure 5), by permission of IOP Publishing/AAS.

**OGLE** Starting with the third phase of the Optical Gravitational Lensing Experiment (OGLE-III, §5.9), a search for planetary transits was initiated using their 1.3-m telescope at Las Campanas, CHL (Udalski et al., 2002a). In 2001, photometric observations of three fields towards the Galactic centre (800 epochs per field) were collected on 32 nights over 45 d (cf. Figure 6.8). Out of 5 million stars monitored, 52 000 with photometry better than 1.5% were analysed for flat-bottomed eclipses with depth  $\lesssim 0.08$  mag. Altogether, 46 low-luminosity transiting objects were detected.

For 42 (185 transits in total), multiple transits were observed, allowing a determination of the orbit period. A total of six campaigns were made between 2001–06 (Udalski et al., 2002b, 2004; Udalski, 2007). Planet candidates were subject to radial velocity follow-up (Dreizler et al., 2002, 2003; Konacki et al., 2003b; Bouchy et al., 2005b; Pont et al., 2005).

These resulted in the first of the confirmed OGLE transiting exoplanets: the hot (1900 K) 1.2-d period  $\sim 1M_J$  mass OGLE-TR-56 (Konacki et al., 2003a; Sasselov, 2003); its secondary eclipse of 0.036% was measured with VLT and Magellan by Sing & López-Morales (2009). Over subsequent years, improved procedures to distinguish between stellar and planet companions were developed (e.g. Silva & Cruz, 2006), and further transiting planets discovered (Appendix D): chronologically, OGLE-TR-113 and OGLE-TR-132 (Bouchy et al., 2004), OGLE-TR-111 (Pont et al., 2004), OGLE-TR-10 (Konacki et al., 2005), OGLE-TR-211 (Udalski et al., 2008) and OGLE-TR-182 (Pont et al., 2008b, see also Figure 6.2). By 2006, of just six transiting planets known in total, five had been detected by OGLE.

A search of the earlier OGLE-II data (1996–2000), using SysRem for detrending and a parameter search using box least-squares (Snellen et al., 2007), resulted in the discovery of OGLE2-TR-L9 (Snellen et al., 2009b). Many follow-up observations, both photometric and radial velocity, have also been made.

Characterisation of stars with small transit depths discovered by OGLE-III, through optical and near infrared photometry, was carried to select the most promising candidates for spectroscopic confirmation (Gallardo et al., 2005, 2010). Radial velocity follow-up showed that the vast majority of transit candidates were eclipsing binaries, with a typical rate of one planet per 10–20 eclipsing binaries. A higher rate of planets is found near the detection threshold, although at the expense of more false-positives (cf. Pont et al., 2008b, their Figure 4). The number of OGLE detections appears broadly compatible with the number expected on the basis of radial velocity surveys (Gould et al., 2006a; Fressin et al., 2007a).

**POTS** The Pre-OmegaTranS project (POTS, see also OmegaTranS) was a deep, 2-min cadence transit survey in the Carina region of the Galactic disk, carried out with the ESO-MPG Wide Field Imager (WFI) at La Silla in 2006–2008 (Koppenhoefer et al., 2013). Two candidates were identified, POTS-1 b and POTS-C2 b, with the former considered confirmed (Koppenhoefer et al., 2013).

**Qatar Exoplanet Survey (QES)** The Qatar Exoplanet Survey contributes a camera system in New Mexico to complement the SuperWASP cameras in the Canary Islands and S. Africa (with a larger aperture, finer pixel scale, and similar field of view). Images and light curves are archived and analysed using methods developed for SuperWASP (Alsubai et al., 2013). By the end of 2017, five planets had been reported (Qatar-1 to Qatar-5), starting with Qatar-1 b (Alsubai et al., 2011) and Qatar-2 b (Bryan et al., 2012), with Qatar-6 reported in early 2018.

**TRAPPIST** The Belgian Transiting Planets and Planetsimals Small Telescope (TRAPPIST) originally comprised a 0.6-m robotic telescope at La Silla, Chile, operational since 2010. It aims to identify transiting exoplanets and comets, as well as monitoring WASP systems (Gillon et al., 2012b; Delrez et al., 2014; Hellier et al., 2014). A second 0.6-m telescope, located in the northern hemisphere at the Oukaimeden Observatory, Morocco, was inaugurated in October 2016 (Manfroid, 2016).

The first discovery, TRAPPIST-1 (box, page 167), was originally discovered as a 3-planet transiting system around an ultracool dwarf at a distance of 12 pc (Gillon et al., 2016), and later recognised as a 7-planet transiting system, with the planets all of terrestrial mass probably orbiting within their habitable zone (Gillon et al., 2017c), although habitability is considered strongly affected by the host star irradiation, stellar wind, and atmospheric loss. Further bibliography is given in Appendix D.

**TrES** The Trans-Atlantic Exoplanet Survey network, no longer operational, initially employed three 0.1-m aperture, wide-field ( $6^\circ$ ), CCD-based systems with an angular resolution of 11 arcsec per pixel. The emphasis was on bright star transits to facilitate follow-up observations (O'Donovan et al., 2006b; Alonso et al., 2007). The telescopes used were STARE (STellar Astrophysics and Research on Exoplanets, Brown & Charbonneau 2000; Rabus et al. 2007), Tenerife, Canary Islands; PSST (Planet Search Survey Telescope, Dunham et al. 2004), Lowell Observatory, Arizona; and Sleuth, Mount Palomar, California); with WATTS, the Wide Angle Transit Telescope Search added later (Oetiker et al., 2010).

Observations were made in Johnson  $R$  or Sloan  $r$ , together observing the same field almost continuously for 2 month intervals. Images were acquired every 2 min, and binned to 9 min resolution. Photometric precision ranged from  $\lesssim 2$  mmag for the brightest non-saturated stars at  $R \approx 8$  to better than 10 mmag at  $R \approx 12.5$ .

Discoveries are TrES-1 to TrES-5 (Alonso et al., 2004; O'Donovan et al., 2006a, 2007; Mandushev et al., 2007, 2011, respectively). The bright host stars has made them important targets for further studies (Appendix D).

**WTS** The WFCAM Transit Survey (WTS) is a near-infrared transit survey running on the United Kingdom Infrared Telescope (UKIRT), designed to search for transiting planets around M dwarfs (Kovács et al., 2013a). It acts as a (poor-seeing) backup programme for the telescope, and is the first dedicated wide-field near-infrared transit survey. Observations in the  $J$ -band began in 2007 in four (seasonal) fields. For low-mass stars, where variability is generally dominated by photospheric star spot activity, operating in the  $J$ -band has the advantage that star spot contrast ratios are minimised (Goulding et al., 2012; Zendejas Dominguez et al., 2013).

Two planets have been reported, WTS-1 b (Cappetta et al., 2012) and WTS-2 b (Birkby et al., 2014).

**XO** Also targeting bright star transits, XO has observed since 2003, concentrating on a large-area survey using two 0.11-m telescopes located on the summit of Haleakala, Maui (McCullough et al., 2005; Burke et al., 2007). The  $1\text{k} \times 1\text{k}$  CCD system operates in drift-scan mode with an instantaneous field of  $7^\circ \times 7^\circ$ . In its first year of operation, for example, XO observed 7% of the sky in  $7^\circ$  wide strips, from  $0^\circ$  to  $+63^\circ$  in dec and centred every 4 h in RA, providing photometry of 100 000 stars at more than 1000 epochs per star, and a precision of 10 mmag per measurement for  $V < 12$  mag. Discoveries to date are XO-1 to XO-6.

#### 6.4.4 Other ground-based surveys

This section summarises other surveys that have not detected planets to date, ordered alphabetically. The compilation includes ongoing surveys, future developments, and efforts that are no longer operational.

A key objective for the 'second-generation' ground-based transit surveys, notably Evryscope and HATPI, and the already-operational MASCARA and NGTS, are wide-field searches for bright star transits, suitable for follow-up and characterisation (e.g. of their structure, tidal evolution, and atmospheric composition), through precision spectrophotometry and mapping, by telescopes such as VLT, E-ELT and JWST.

- **ASTEP (Antarctic Dome C)**: the 'Antarctica Search for Transiting Extrasolar Planets', with institutes from FRA/CHE, conducted its first transit observations with a 0.4-m automatic telescope at Dome C, which targets observations to  $V = 16$  (Fressin et al., 2005, 2007b; Crouzet et al., 2010a; Daban et al., 2010; Guillot et al., 2015). WASP-19 was observed during 24 nights in May 2010, with detection of the secondary eclipse reported by Abe et al. (2013c). Observations of WASP-18 in 2010 were reported by Fruth et al. (2014). During the 2010–12 operations, 43 planetary transit candidates were detected (Mékarnia et al., 2016).

- **AWCam (Arctic Wide-field Cameras)**: two developments at Canada's Eureka research base (at  $80^\circ$  N on Ellesmere Island, Canadian High Arctic), and the nearby (600-m altitude) Polar Environmental Research Laboratory (PEARL, Ridge Lab), are intended to exploit the site's continuous winter darkness and high-photometric precision (Law et al., 2012).

The Dunlap Institute Arctic Telescope (DIAT) is a 0.5-m wide-field imaging telescope searching for transiting planets in the habitable zone of 10 000 M dwarfs at 30-min cadence. Some 500 M dwarfs are targeted in each field, and several sets of target fields are planned to be imaged throughout the Arctic winter.

The AWCams are two small telescopes searching for bright star transits ( $V = 5 - 10$ ), and considered as High-Arctic prototypes of the individual Evryscope cameras. They comprise large low-cost front-illuminated CCDs behind DSLR camera lenses. They were deployed to the PEARL station in early 2012 (Steinbring et al., 2012a; Law et al., 2012; Steinbring et al., 2012b; Law et al., 2013). The two cameras stare at 500–1000 sq. deg around the North Celestial Pole, monitoring 70 000 bright stars, and taking short 10-s exposures to avoid the need to track. The AWCams have been operated for three winters, including a test run in 2012 February, and full-winter (unattended) operations in the 2012–13 and 2013–14 winters. The cameras kept themselves and their windows clear of snow and ice, and took over 40 TB of images. The AWCam pipeline achieves scintillation-limited photometric precision in each exposure, with binning bringing it to  $\sim 3$  mmag in 10 min. A dark period in winter 2012–13 attained 3–4 mmag stability over an uninterrupted period of 480 h (Law et al., 2014a). The individual AWCams cover only  $\sim 5\%$  of the sky continuously accessible from the Ridge Lab in winter months. CATS (the Compound Arctic Telescope Survey) is a conceptual design for a compound telescope system comprising a number of wide-field cameras mounted in a common enclosure, to search over a larger sky area (Law et al., 2012).

- **BOKS**: the Burrell Optical Kepler Survey was a 40-night ground-based campaign of time series photometry of a  $1.39 \text{ deg}^2$  field located within the Kepler mission's field of view. The goal of this pre-launch survey was to search for transiting planets and to provide independent variability information on the stellar sources (Feldmeier et al., 2011). The data set contained light curves of 54 687 stars, and a preliminary catalogue of 2457 candidate variable stars, of which 776 show signs of periodicity, with three exoplanet candidates (Howell et al., 2010).

**Individual transiting objects of note, discovered from radial velocity surveys:**

- 30 Ari Bb** discovered by Guenther et al. (2009), with transits subsequently found in the Hipparcos data (Kane et al., 2015a).
- 55 Cnc e** 5-planet system, originally discovered by Butler et al. (1997), with transits of planet e detected from MOST (Winn et al., 2011c).
- GJ 436 b** hot Neptune-mass planet with large eccentricity (Butler et al., 2004b), and with transits discovered from the 0.6-m Swiss OFXB telescope (Gillon et al., 2007b). Subsequent developments are detailed by Stevenson et al. (2012b).
- GJ 3470 b** discovery, and transits discovered from TRAPPIST (Bonfils et al., 2012).
- HD 17156 b** long-period ( $P = 21.2$  d), high eccentricity ( $e = 0.67$ ) planet, discovery by N2K–Subaru (Fischer et al., 2007a), with transits discovered from Italy/Canaries (Barbieri et al., 2007).
- HD 80606 b** discovery by Naef et al. (2001a), with transits discovered from OHP (Moutou et al., 2009a), Esteve Duran Observatory (Garcia-Melendo & McCullough, 2009), and UCL Observatory (Fossey et al., 2009).
- HD 97658 b** radial velocity discovery with Keck–HIRES (Howard et al., 2011b), with transits discovered from Fairborn–APT (Henry et al., 2011a), contested, but subsequently confirmed by MOST, Spitzer and HST (Dragomir et al., 2013; Van Grootel et al., 2014; Knutson et al., 2014b).
- HD 149026 b** small hot Saturn-mass ( $0.37M_J$ ) planet, with radial velocity discovery from N2K–Subaru and transits discovered from Fairborn–APT (Sato et al., 2005a).
- HD 189733 b**  $1.1M_J$  planet orbiting nearby (19 pc) K0 star at  $a = 0.03$  au. The host star is the primary of a binary system, secondary is an M dwarf at 216 au. Radial velocity discovery was with OHP–ELODIE, and transits from OHP were reported at the same time (Bouchy et al., 2005c), with *a posteriori* detection in the Hipparcos photometry (Hébrard & Lecavelier des Etangs, 2006). It is an important target for transmission and emission spectroscopy, and atmospheric characterisation.
- HD 209458 b** planet with  $P = 3.52$  d,  $M_p \sin i = 0.62M_J$ ,  $R_p = 1.32R_J$ ,  $a = 0.046$  au, transiting a  $1.1M_\odot$  G0 dwarf at 47 pc, with  $\Delta F = 0.017$  mag. The discovery was through radial velocity with Keck–HIRES (Henry et al., 2000). Transit detection was reported from Fairborn–APT (Henry et al., 1999, 2000) and by STARE (Charbonneau et al., 2000), with *a posteriori* detection in the Hipparcos photometry (Söderhjelm et al., 1999; Robichon & Arenou, 2000; Castellano et al., 2000). It is an important target for transmission and emission spectroscopy, and atmospheric characterisation.
- HD 219134 b** a low-mass 4-planet system around a bright ( $V = 5.5$ ) nearby (6.5 pc) star, the first result of the Rocky Planet Search programme with HARPS–N on La Palma–TNG, and with transits discovered from Spitzer (Motalebi et al., 2015).

• **CSTAR (Antarctic Dome A):** the ‘Chinese Small Telescope ARray’ comprises four automated 0.14-m telescopes at Dome A, the highest point on the Antarctic plateau. Covering  $20 \text{ deg}^2$  around the South Celestial Pole, it targets high-cadence monitoring of observing conditions, and transit detections. Operational since 2008, Yuan et al. (2010) described its performance over three Antarctic winters. Wang et al. (2014d) reported photometry of 10 690 stars (291 911 observations of 20 s integrations in the  $i$  band), reaching 4 mmag precision at 20 s cadence at  $i = 7.5$ , and 20 mmag at  $i = 12$ . Of 10 exoplanet candidates, four were found to be giants based on spectroscopic follow-up.

• **Evryscope:** a single ‘mushroom array’ of twenty-four 0.061-m telescopes, covering the accessible sky simultaneously, together forming a Gpix telescope monitoring an overlapping 8000 sq. deg. field every 2 min (Law et al., 2014b, 2015). Funded by NSF/ATI, it has been operating at CTIO since 2015 May. Both Arctic and Antarctic options have been proposed. For exoplanet science (Fors et al., 2015), Evryscope aims to exploit its very large field to search for exoplanets around nearby bright stars, to conduct a habitable-zone survey for rocky transiting planets around nearby M dwarfs, to conduct a transit survey for the very deep eclipses of bright nearby white dwarfs, and to assist TESS through long-term monitoring of its target stars.

• **GPX:** an amateur designed Galactic Plane Exoplanet survey, based in Acton (Ma), and designed to search high density star fields (Benni, 2017).

• **HATPI:** from its observing site at Las Campanas, Chile, HATPI aims to observe the majority of the visible night sky in a single exposure. It is expected to observe some 100 million sources over 5 yr, with a cadence of 30 s, and a photometric precision

of 3 mmag for the brightest. It comprises 63 lens–camera sub-units attached to a single mount, continuously tracking the sky. In addition to exoplanet transits, HATPI will survey near-Earth asteroids, novae, and bright gamma-ray bursts. HATPI is expected to be partially operational in 2018.

• **ICE–T (Antarctic Dome C):** the International Concordia Explorer Telescope, with institutes from DEU/ITA/ESP, was a proposed design for a dual 0.6-m wide-field Schmidt telescope at Dome C, with a focus on transits, and a goal of detecting planets of a few  $M_\oplus$  in habitable zones (Strassmeier et al., 2007).

• **LSST:** the 8.4-m Large Synoptic Survey Telescope is a 3-mirror active optics telescope under construction on Cerro Pachón, northern Chile (LSST, Ivezić et al., 2008). With a 3.2-Gpix camera,  $3^\circ 5$  field, and an étendue of  $319 \text{ m}^2 \text{ deg}^2$ , it will produce a 6-band (0.3–1.1  $\mu\text{m}$ ) wide-field survey over  $30\,000 \text{ deg}^2$ , addressing cosmology, Galactic structure, and solar system. Each region will be visited 1000 times ( $2 \times 15$  s exposures) in 10 yr, for a total of  $20 \times 10^{12}$  measurements of 20 billion sources. Site construction began in April 2015. Engineering first light is scheduled for 2020. The 10-year survey should start in January 2023.

Its temporal sampling is not optimised for transit characterisation, although detection prospects are substantial, ranging from hot Jupiters around solar-type stars (perhaps to the LMC), to super-Earths in the habitable-zone of M dwarfs (Jacklin et al., 2015, 2017). Some 27 000 hot Jupiters could be observed in transit between 16–22 mag, with  $\sim 1000$  discoveries assuming that 5% are recovered (Lund et al., 2015a).

• **OmegaTrans:** the OmegaCam Transit Survey was a collaboration between INAF–Capodimonte, Sterrewacht Leiden, and MPE Garching, initiated in 2004, with 26 nights guar-

anteed time with OmegaCam at the ESO–VLT Survey Telescope (VST). Conceived when only 8 transiting exoplanets were known, it was expected to discover 10–15 new planets per year. Due to delays in telescope construction and commissioning, OmegaTranS was finally canceled, to be replaced by the Pre-OmegaTranS survey, POTs (§6.4.3).

- *Pan-STARRS*: is a 1.8-m f/4 Ritchey–Chrétien telescope and 1.4 Gpix CCD camera in Hawaii, with an étendue of  $13 \text{ m}^2 \text{ deg}^2$ . The camera contains a  $64 \times 64$  array of orthogonal transfer CCDs, each  $600 \times 600$  pixels, and uses five wide bands spanning  $0.4\text{--}1.0 \mu\text{m}$ . The primary science driver is a 30 000  $\text{deg}^2$  northern hemisphere survey of near-Earth 1-km size objects, although many other applications are possible. The first of four originally-proposed telescopes, PS1 began operations in May 2010. The sparsely time-sampled Pan–STARRS–1 multiband  $3\pi \text{ sr}$  survey may detect single epoch transits from Jupiters transiting M dwarfs (Dupuy & Liu, 2009).

The Pan–Planets survey was originally foreseen to use the telescope to cover 21 sq. deg. over four years to  $i = 16\text{--}17 \text{ mag}$ . With 120 h of observations per year and 6 min time sampling, some 100 hot Jupiters were predicted (Afonso & Henning, 2007; Koppenhoefer et al., 2009). Obermeier et al. (2016b) provided an interim report on a 165-h, 42 sq. deg. survey of the Galactic disk, targeting the detection of transiting planets around M dwarfs. They identified 60 000 M dwarfs, and a number of planet candidates are under investigation.

- *PTF*: the Palomar Transient Factory employs a 92 Mpix  $7.3 \text{ sq. deg.}$  camera at the 1.2-m Oschin Telescope at Palomar Observatory (Rau et al., 2009; Law et al., 2009, 2011). Targeting optical transient and variable sources, it was commissioned in mid-2009. PTF focuses on a search for transiting planets in Orion. A candidate around the T Tauri star PTF0 8–8695 (CVSO 30), based on 17 transits (van Eyken et al., 2012), was confirmed by Barnes et al. (2013a), and is the first transiting candidate orbiting a pre-main-sequence star (§6.19.5). PTF/M-dwarfs is an M dwarf transit survey also carried out with PTF. Each *R*-band image contains  $\sim 3000$  M dwarfs, and in each season, searches are made for Jupiter-radius planets around 30 000, Neptune-radius planets around 500, and super-Earths around 100. The survey, running since 2009, should cover 100 000 targets over the coming years (Law et al., 2011).

- *SAINT-EX*: the ‘Search and chAracterisAtion of Transiting EXoplanets’ instrument is a 1-m transit telescope under construction at San Pedro Martir, Baja California.

- *SkyMapper*: is a 1.35-m telescope with f/4.8 optics and a  $32 \text{ k} \times 4 \text{ k}$  CCD camera, sited at Siding Spring Observatory (Coonabarabran, NSW Australia), and building on the SuperLupus search (Keller et al., 2007; Bayliss & Sackett, 2007). The telescope has a  $5.2 \text{ deg}^2$  field of view, and an étendue of  $5.2 \text{ m}^2 \text{ deg}^2$ , and aims to survey a billion stars and galaxies in the southern hemisphere. Its 1-min exposures will tile each part of the sky 36 times in multiple optical bands. Commissioning was reported by Tyson (2010).

- *SPECULOOS*: the ‘Search for habitable Planets Eclipsing ULtra-coOL Stars’ transit instrument comprises four 1-m robotic telescopes at Paranal, Chile, optimised for detecting Earth-size planets transiting the nearest (targeted) ultra-cool dwarfs (Gillon et al., 2013b; Queloz, 2015). Concept validation has been through a 2011 survey monitoring the 50 brightest southern ultra-cool stars, UCDS (Ultra-Cool Dwarfs Transit Survey) using the ESO–TRAPPIST telescope (Jehin et al., 2011). First light was targeted for late 2017.

- *Subaru Suprime-Cam*: the instrument has been used to mon-

itor 100 000 stars in the Galactic plane to assess its suitability for fainter transit surveys to beyond 18 mag (Urakawa et al., 2006).

- *VISTA*: is a 4-m wide field near-infrared southern hemisphere survey telescope, located at ESO’s Cerro Paranal Observatory, Chile (Sutherland et al., 2015). It is equipped with 16 hybrid CMOS HgCdTe arrays totaling 67 Mpix of size  $0.34 \text{ arcsec}$  ( $0.6 \text{ sq. deg.}$  per exposure), and an étendue of  $6.8 \text{ m}^2 \text{ deg}^2$ . It is equipped with five broad-band filters covering  $0.85\text{--}2.3 \mu\text{m}$ , and a narrow-band filter at  $1.18 \mu\text{m}$ . Science operations began in December 2009. Further details are given in Section 9.2.2.

- *YETI*: the Young Exoplanet Transit Initiative is a global network monitoring young (2–200 Myr) nearby clusters for young transiting planets (Neuhäuser et al., 2011; Raetz et al., 2015).

**Antarctic/Arctic advantages** Transit observations from the Antarctic or high Arctic would advance two of the limitations of ground-based surveys: limited (diurnal-cycle) time sampling, and systematic atmospheric photometric variations on time scales of hours. Tests and site characterisation have assessed the suitability of the Antarctic plateau, including Dome C at  $-75^\circ$  latitude (see also Section 7.6.4), for photometric time series observations in general, and for planet transit detection in particular (e.g. Viotti et al., 2003; Caldwell et al., 2004; Pont & Bouchy, 2005; Crouzet et al., 2009, 2010b).

Rauer et al. (2008) compared performances with a site in Chile, and a lower-latitude three-site network, concluding that Dome C is a prime site for long-duration observations during winter, nonetheless best operated as part of a network. Further comparisons with similar conclusions have been reported by Fruth et al. (2014). Relevant instruments in both the Arctic (AWCam) and Antarctic (ASTE, CSTAR, and ICE-T) are listed under their specific instrument names.

## 6.5 Searches from space: CoRoT

**Satellite** The CoRoT satellite, led by CNES (F) with several international partners (ESA, Austria, Belgium, Brazil, Germany and Spain), was launched on 2006 December 27 into a 900 km altitude, 103-min polar orbit, and was dedicated to both stellar seismology and the search for transiting exoplanets (Auvergne et al., 2009; Lammer et al., 2010; Deleuil, 2012; Moutou et al., 2013b).

The telescope has an effective diameter 0.27 m, the field of view is  $2^\circ 7' \times 3^\circ 0'$ , and the focal plane comprises four  $2 \text{ k} \times 2 \text{ k}$  CCDs. The measured attitude stability is  $\sim 0.15 \text{ arcsec rms}$ . The polar orbit gives two preferred viewing directions separated by  $180^\circ$ , in the directions of the Galactic centre and anti-centre, each of which can be observed continuously for up to 150 days, with at least five different fields planned over the mission lifetime. In the planet transit search mode, some 12 000 target stars are observed simultaneously.

Observations were originally scheduled for 2.5 years. Operations were extended to 2013, although a computer failure on 2012 November 2 led to mission termination on 2013 June 24. Over its lifetime, CoRoT observed more than 20 different star fields for up to a maximum of 150 d, collecting photometric data on  $\sim 175 \text{ 000}$  stars.

Stars were sampled with a cadence of either 512 s or 32 s, and the photometric signal is extracted on board

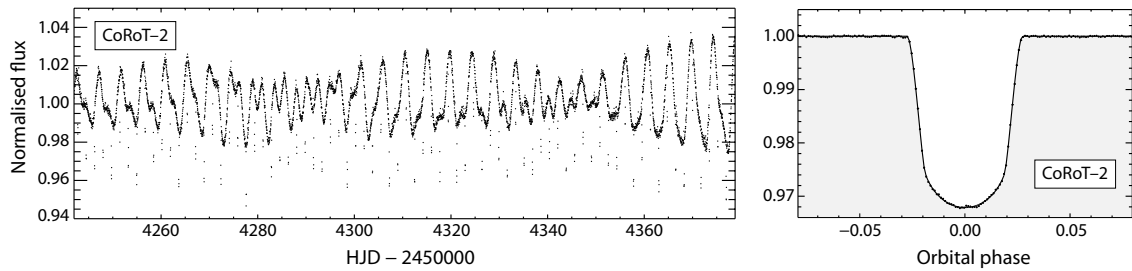


Figure 6.9: CoRoT-2. Left: normalised flux over 150 d, showing 78 orbital periods with a resolution of 34 min. The prominent low-frequency modulation is due to spots on the stellar surface. Right: phase-folded light curve of the 78 transits with a time resolution of 2.5 min. The planetary parameters are  $P = 1.742996$  d,  $i = 87^\circ 84$  and (in combination with radial velocity data)  $M_p = 3.31 M_J$ ,  $R_p = 1.465 R_J$ ,  $\rho = 1.31 \text{ Mg m}^{-3}$ . From Alonso et al. (2008a, Figures 1–2), reproduced with permission © ESO.

using optimised apertures selected for the target stars. A dispersing prism allows brighter stars to be measured in three channels (red, green, blue), assisting discrimination of planet transits from the more chromatic stellar variability. For the remainder, samples are combined into a single white light channel.

**Observations** The first long observation run, LRC01 towards the Galactic centre in the direction of Aquila, lasted from 2007 May–October (Cabrera et al., 2009). Measured photometric precision is  $7.1 \times 10^{-4}$  at  $R = 15$  mag for 512 s sampling, with the photon-limited photometric accuracy typically ranging from  $\sim 75$  ppm in a 1-h integration to  $\sim 1130$  ppm  $\text{h}^{-1}$  for  $11 < R < 16$  (for details of noise properties and related calibration issues, see Aigrain et al., 2009; Alapini & Aigrain, 2009; Mazeh et al., 2009a). Photometric analysis resulted in 42 candidates, of which 26 were settled by mid-2009, leading to a subset of confirmed planets and 16 open cases; the non-planets are either binaries, grazing binaries, or contaminating systems where light from an eclipsing binary is blended with light from a nearby star (Almenara et al., 2009). The first long run in the Galactic anti-centre direction, LRA01, ran from 2007 October to 2008 March.

The topics of detrending and transit detection are treated more generally in Section 6.12.

**Follow-up observations** As for ground-based surveys, extensive photometric and radial velocity follow-up observations were required, both for candidate verification (Nefs et al., 2012) and detailed system characterisation. CoRoT routinely made use of, amongst others, radial velocity observations from ESO–HARPS, OHP–SOPHIE, Keck–HIRES, and the low-resolution spectrograph of the Thüringer Landessternwarte Tautenburg (DEU), as well as instruments from IAC (ESP), McDonald (USA), Wise (ISR), Leonard Euler time of the Geneva Observatory (CHE), VLT–UVES/GIRAFFE, BEST II (DEU), and ESA’s optical ground station in Tenerife (Loeillet et al., 2008a; Santerne et al., 2011c). Transit duration, planet size, and orbital eccentricity can be significantly improved us-

ing follow-up photometry on the ground (Colón & Ford, 2009; Deeg et al., 2009). BEST allowed the ‘precovery’ (pre-discovery recovery) of transits of both CoRoT-1 and CoRoT-2 (Rauer et al., 2010).

The precision with which planetary parameters can be measured from the photometry relies on the precision of stellar parameters, of which limb darkening is partially degenerate with the orbit inclination. The limb darkening is therefore preferably established independently (Torres et al., 2008), for example using *BVRI*, and *JHK<sub>s</sub>* from 2MASS, which provides the temperature and spectral class, and hence model limb-darkening coefficients. Their Exo-Data database, providing prior knowledge and other complementary information, is described by Deleuil et al. (2009). Public access details are described by Solano et al. (2009).

**Designation** Early discoveries were assigned designations CoRoT–Exo–NNN, while the form CoRoT–NNN was adopted after 2009 March.

**Discoveries** CoRoT has discovered a number of confirmed planets, CoRoT-1 b to CoRoT-33 b. An example light curve, for CoRoT-2 b, is shown in Figure 6.9. This is representative of a number of systems which show a clear transit signal on top of a significant semi-periodic rotational variation of stellar flux due to star spots.

CoRoT planets range in mass from  $0.02 M_J \sim 5 M_\oplus$  (CoRoT-7 b, CoRoT-24 b) up to objects in the brown dwarf range. Radii are between  $0.14 R_J$  (CoRoT-7 b) to  $1.5 R_J$  (CoRoT-1 b), with densities between  $0.15 \text{ Mg m}^{-3}$  (CoRoT-25 b) to  $12 \text{ Mg m}^{-3}$  (CoRoT-27 b), including rocky planets with  $\rho \sim \rho_\oplus$  (CoRoT-7 b). Orbital periods range from 0.8 d (CoRoT-7 b) to 95 d (CoRoT-9 b).

There are two 2-planet systems, CoRoT-7 (in which CoRoT-7 c was discovered from radial velocities), and CoRoT-24 (in which both planets transit). The Rossiter–McLaughlin effect has been measured in at least CoRoT-1 b, CoRoT-2 b, CoRoT-3 b, and CoRoT-11 b.

Star spots detected in CoRoT-2 b and CoRoT-7 b allow detailed models of stellar rotation and obliquities.



**Individual CoRoT objects of note:**

**CoRoT-2** the planet orbits one of the most active stars known to host a transiting exoplanet, covered with cool spots, and important for studying magnetic field interaction, stellar rotation, and orbital obliquity (Alonso et al., 2008a; Walker et al., 2008). The planet has a large inflated radius, and observations at 4.5  $\mu\text{m}$  show an unexpected westward-shifted hot spot with respect to the sub-stellar point (Dang et al., 2018).

**CoRoT-3** a brown dwarf in the brown dwarf desert: ground-based Doppler measurements have established that there is a paucity of brown dwarfs ( $\sim 13 - 60M_J$ ) in relatively short-period orbits, the *brown dwarf desert*. CoRoT discovered at least three objects in this 'desert', including the first secure inhabitant CoRoT-3 b, with  $22M_J$ ,  $R \sim R_J$  (Deleuil et al., 2008). Ellipsoidal and relativistic beaming effects were detected by Mazeh & Faigler (2010).

**CoRoT-7** 2-planet system, in which planet c was discovered through radial velocity follow-up. CoRoT-7 b was the first transiting rocky planet, with  $P = 20.5$  h and a particularly shallow transit depth of 0.03%, attributed to a planet with  $R \sim 1.6R_\oplus$  (Léger et al., 2009). Radial velocity measurements determined the mass of CoRoT-7 b as  $6 - 7M_\oplus$  (Hatzes et al., 2011; Barros et al., 2014a), corresponding to  $\rho = 10.4 \pm 1.8 \text{ Mg m}^{-3}$ , possibly making the structure of CoRoT-7 b closer to that of Mercury than that of Earth. CoRoT-7 b gave the first indication that rocky planets can have ultra-short period orbits ( $P < 1$  d).

**CoRoT-9** before the launch of Kepler, CoRoT's planets accounted for half of transiting systems with orbital periods greater than 8 d. Particularly extreme in orbital period, CoRoT-9 b is in a 95-d orbit, and the first transiting giant planet discovered with a moderate brightness temperature,  $\sim 300$  K (Deeg et al., 2010). Although most hot Jupiters have anomalously large radii of  $1.3 - 1.5R_J$ , CoRoT-9 b has a less-inflated radius ( $1.01R_J$ ), consistent with a lower radiation flux from the host star ( $\$6.28.4$ ).

**CoRoT-20** is a giant planet with an unusually small radius. Planetary evolution models suggest that its interior should contain a very large amount of heavy elements, with a central dense core of mass  $680 - 1040M_\oplus$  (Deleuil et al., 2012). Although mixing heavy elements in the envelopes rather than confining them to a central core can lead to substantially smaller values (by a factor of 2-3), the origin of such a significant amount of heavy elements is difficult to explain with current models. From tidal stability analyses, CoRoT-20 b belongs to the small population of transiting planets that are considered as 'Darwin-stable' ( $\$10.11.4$ ), i.e. systems for which in the absence of processes extracting angular momentum from the system (i.e. stellar winds), the planet would never fall onto the central star, which would instead be spun-up and achieve triple-synchronisation (equality of the orbital, planetary, and stellar spin periods).

**CoRoT-21** a  $P = 2.7$  d,  $2.3M_J$  planet with extreme tidal forces leading to orbit decay in  $\sim 800$  Myr (Pätzold et al., 2012).

**CoRoT-24** 2-planet system, in which both transit (the only such CoRoT system) with  $P = 5.1$  d and  $11.8$  d (Alonso et al., 2014).

**CoRoT-29** asymmetric transits, attributed to either an underlying oblate star or to spots (Cabrera et al., 2015).

CoRoT-3 b ( $22M_J$ ) and CoRoT-33 b ( $59M_J$ ) populate the brown dwarf desert ( $\$2.10.5$ ), bridging the gap between gas giants and low mass stars.

From the perspectives of planetary structure and evolution, CoRoT has provided insight into the variety of internal structures found in close-in giant planets, as well as providing constraints on their formation, evolution, and the role of tides (Moutou et al., 2013b).

**Individual objects** Some specific CoRoT systems of note are given in the box on page 173, and a bibliography of all discoveries is given in Appendix D.

**Secondary eclipses** Secondary eclipses in the CoRoT data were initially reported for CoRoT-1 b (Snellen et al., 2009a; Alonso et al., 2009a), subsequently confirmed by Earth-based observations in the near infrared (Rogers et al., 2009; Gillon et al., 2009b; Zhao et al., 2012c), and CoRoT-2 b (Alonso et al., 2009b), also subsequently confirmed from the ground (Alonso et al., 2010).

Parviainen et al. (2013) made a homogeneous search for secondary eclipses in the original data of all published CoRoT planets, using a Bayesian model as a function of the secondary eclipse mid-time. They found significant eclipses for two further planets, CoRoT-6 b and CoRoT-11 b, and for the brown dwarf CoRoT-15 b, with others of more marginal significance. From these, at-

mospheric temperatures, albedos, and energy redistribution parameters have been inferred ( $\$6.24$ ).

**Mass-density relation for CoRoT planets** Over two orders of magnitude in mass ( $M_p \sim 0.3 - 20M_J$ ) the CoRoT planets follow a tight power law (Figure 6.10)

$$\rho = (0.73 \pm 0.1) M_J^{1.17 \pm 0.11}. \quad (6.2)$$

This nearly linear correlation of density with mass reflects the fact that all objects ranging from giant planets ( $\sim 1M_J$ ) to low-mass stars ( $\sim 100M_J$ ) have about the same radius. Thus, an increase in mass is accompanied by a proportional increase in density. This is expected as the pressure support in giant planets is provided by electron-degeneracy. Stars, however, have their pressure support provided by hydrogen burning under hydrostatic equilibrium.

Two outliers deviate from this power law relationship by  $\sim 4\sigma$ : CoRoT-13 b and CoRoT-20 b. These planets have anomalously high densities for their respective sizes. One hypothesis is that these may be the merger of two more 'normal' giant planets (Deleuil et al., 2012).

**CoRoT versus Kepler** The observational programmes of CoRoT and Kepler differed in two main ways. First, Kepler emphasised Sun-like stars, whereas CoRoT obtained data on most stars in its field, including many

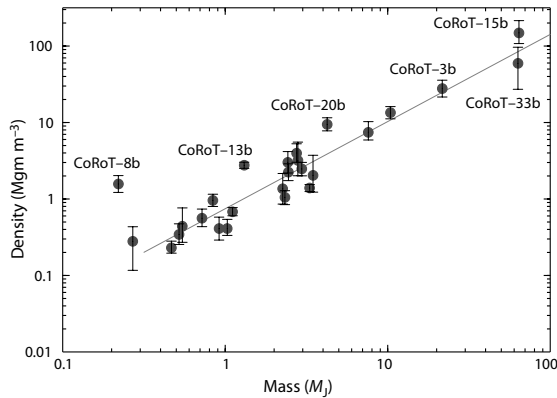


Figure 6.10: Mass–density relation for the 26 CoRoT giant planets. The line is a power law fit,  $\rho = 0.73 M_J^{1.17}$ . The outliers CoRoT-8b, CoRoT-13b and CoRoT-20b are indicated. From Hatzes (2014b, Figure 1), by permission from Nature/Springer/Macmillan Ltd, ©2014.

non-solar like stars. Second, they observed in different directions in the Galaxy: Kepler observed a field near Cygnus, just out of the Galactic plane, while CoRoT observed two regions in the Galactic plane, one towards the Galactic centre, and the other towards the anti-centre. The latter results in expected population differences (e.g. Girardi et al., 2015).

These differences may explain the larger fraction of CoRoT’s discoveries around relatively young host stars (some 35% of the CoRoT planets orbit F-type stars, compared to Kepler’s 20%). They may also explain the lower fraction of Neptune-size planets found from CoRoT compared to Kepler (Bonomo et al., 2012a).

## 6.6 Searches from space: Kepler

The Kepler satellite, dedicated to exoplanet transit discovery and characterisation, has transformed the field of exoplanet research, not only because of the very significant numbers of exoplanets discovered (numbered in the thousands), but even more so because of the richness and unexpected nature of the planetary system architectures, and the deep insights into the broad range of physical phenomena that have been gained.

Like all transit searches, Kepler identifies exoplanets whose orbits happen to lie edge-on by searching for periodic dips caused by transits across the stellar disks.

**Overview** Kepler evolved from the FRESIP concept, which was unsuccessful in its initial bid as part of NASA’s Discovery Program (Koch et al., 1996). In its evolved form, Kepler was selected as the tenth Discovery mission, and launched on 2009 March 6 into an Earth-trailing heliocentric orbit (Borucki et al., 2010a; Koch et al., 2010a; Lissauer et al., 2014a; Borucki, 2016, 2017).

It comprises a 0.95 m aperture modified Schmidt

telescope, and 42 2048 × 1024 CCDs covering a wide field (115 sq. deg.) over the wavelength range 430–890 nm.

In its prime mission phase, Kepler monitored 150 000 main sequence stars (8–15 mag) in Cygnus, at 30-min cadence, continuously for nearly four years.

Kepler began its photometric monitoring campaign in 2009 May. The prime mission ended in 2013 May with the failure of a second reaction wheel in the attitude control system. A revised K2 phase, which began on 2014 May 30, is described in Section 6.6.3.

**Designations** Various identifiers (EPIC, KIC, KOI) designate the different stages in the candidate identification process, with the identifier Kepler–NNN assigned by the project only when a candidate is considered to be confirmed (box, page 175).

The identifiers Kepler–1 to 3 were reserved for the three planetary systems already known to be in the Kepler field before launch (TrES–2, HAT–P–7, and HAT–P–11 respectively) and are therefore, according to discovery precedence, identifiers rarely encountered.

**Pre-launch objectives** Kepler’s pre-launch objectives (Borucki et al., 2007) were to explore the structure and diversity of exoplanet systems in order to determine:

- the frequency of Earth-size and larger planets in or near the habitable zone across various spectral types;
- the distributions of size and orbital semi-major axes;
- the frequency in multiple-star systems;
- the distributions of semi-major axis, albedo, size, mass and density of short period giant planets; and
- the properties of stars harbouring planetary systems.

Pre-launch simulations suggested that a population of hot super-Earths should be detectable (Schlaufman et al., 2010). In addition to transits, some 100 reflected light detections were predicted for planets with orbital periods up to 7 days (Jenkins & Doyle, 2003).

### 6.6.1 Instrument details

**Detectors and sampling** Kepler employed 42 CCDs covering a 115 deg<sup>2</sup> field of view, for which the high photometric precision requires detailed knowledge of the pixel response. Each pixel spans 3.98 arcsec, and while the telescope is at an optimal focus that minimises the point spread function across the focal plane, local regions have non-optimal response.

Spacecraft pointing stability is 0.2 arcsec (0.05 pixels) over a 90-d quarter. Spacecraft velocity-induced stellar aberration varies across the field, resulting in differential aberration, and thus positional shifts on the detector, by up to 2.4 arcsec (0.6 pixels) over a quarter (Batalha et al., 2010a; Coughlin et al., 2014).

The *pixel response function* is the combination of the telescope’s optical point spread function, the CCD pixel response, and the spacecraft pointing jitter. Their combination results in a pixel response function with a 95%

**Identifiers – Kepler, KIC, KOI, EPIC:** The Kepler identification, or Kepler ID, is the target identification number in the Kepler Input Catalogue (KIC, Brown et al., 2011b). The KIC was derived from a ground-based imaging survey of the Kepler field conducted prior to launch, aiming to identify stars for the Kepler survey by magnitude and colour. The full catalogue of 13 million sources is further restricted to some 4 million targets found on the Kepler CCDs.

A ‘Kepler Object of Interest’ number, assigned by the Kepler project, identifies a target with at least one transit-like sequence of astrophysical origin and initially consistent with a planetary transit. Having the format KNN.DD, the integer part designates the target star; the two-digit decimal part identifies a unique transiting candidate associated with that star.

Kepler numbers are of the form Kepler–NNN, designating the host star, plus a lower case letter identifying the planet. Kepler numbers are assigned, by NASA Exoplanet Archive science staff, to candidates that have been confirmed or validated as planets (either through a dynamical analysis confirming the mass, or a statistical analysis favouring its probability), and which appear in peer-reviewed papers.

The KOI numbers, rather than the Kepler numbers, preserve information on the statistical integrity of the planet samples in terms of limits and biases. For this reason, candidates discovered by ‘external pipelines’ are not assigned KOI numbers, even if subsequently confirmed and assigned a Kepler number (e.g. Kepler–78 b). On the other hand, improvements in the official Kepler pipeline are made following external studies, leading to the assignment of new KOI numbers.

Although early papers often refer to candidates by the KOI (or even KIC) number, Kepler–NNN numbers are used preferentially here. Tables with all assigned Kepler numbers, and the full catalogue (including KOI numbers), are available at [exoplanetarchive.ipac.caltech.edu](http://exoplanetarchive.ipac.caltech.edu).

Of more than 2300 confirmed Kepler–NNN designated systems, the NASA Exoplanet Archive retains the KIC number as default identifier for 7, and the KOI number as default identifier for 9 (see Appendix D).

The EPIC (Ecliptic Plane Input Catalogue) identifier is a similar construct to the KIC, providing coordinates, photometry and kinematics based on a federation of all-sky catalogues to support target selection and management for the K2 mission extension (Huber et al., 2016).

encircled flux radius of 16–28 arcsec (4–7 pixels), with an increasingly asymmetric response towards the edge of the field of view (Bryson et al., 2010a). Sub-pixel resolution is represented as a piecewise-continuous polynomial on a sub-pixel mesh (Bryson et al., 2010b). The resulting lower envelope of the photometric precision at various time scales is largely consistent with expected random noise, yielding high precision over a large dynamic range (Caldwell et al., 2010; Jenkins et al., 2010b).

Due to onboard storage and bandwidth constraints, only 5.44 million (5.4%) of the 96 Mpix (Bryson et al., 2010a), or 170 000 of the 500 000 stars (34%) with Kepler magnitude brighter than 16.0 (Batalha et al., 2010a), could be downloaded from the spacecraft to ground.

**Long- and short-cadence data** Kepler data are available in two cadences, long and short. Each is composed of multiple 6.02-s exposures with their associated 0.52-s readout times (Haas et al., 2010; Jenkins et al., 2010b; Gilliland et al., 2010; Murphy, 2012). The short cadence data integrate 9 exposures to give one data point every 58.9 s. The long cadence data integrate 270 exposures to give one point every 29.4 min. Both were stored onboard and downlinked to Earth roughly every 32 d, introducing data-collection gaps of up to 24 h.

Kepler completed one quarter of its orbit after three downlinks, then performed a quarterly roll to maintain the solar panels Sun-pointing, and the radiator pointing to deep space. Kepler data are therefore organised into quarters and thirds around those rolls and downlinks. Long cadence data quarters are denoted by Q<sub>n</sub>, and short cadence quarters by Q<sub>n</sub>.m to notify which third (or ‘month’) of that quarter the data correspond to.

**Data processing** An overview of the various steps of the data processing are given in subsequent sections, in particular for detrending (§6.12.1), transit detection (§6.12.2–6.12.3), light-curve fitting (§6.12.4), and candidate confirmation (§6.12.5).

While some software algorithms related to specific steps of the data processing are referenced in these sections, a more detailed compilation of software tools created by the Kepler/K2 Guest Observer Office is also available online (see Table 1.4).

### 6.6.2 Target stars and accuracies

**Sample selection** Kepler’s selected sample of around 170 000 stars was chosen from the 500 000 or so in the field of view that are brighter than 16 mag (Batalha et al., 2010a). Selection criteria were designed to optimise the scientific yield of the mission with regard to the detection of Earth-size planets in the habitable zone. The selection yielded ~140 000 stars on or close to the main sequence, of which more than 90 000 are G type, of which more than 20 000 are brighter than 14 mag. At the temperature extremes, the sample also includes ~3000 M dwarfs, a small number (~200) of O- and B-main sequence stars, and ~5000 giants with  $\log g < 3.5$ , along with a number of known eclipsing binaries, open cluster members, and high proper motion stars.

Three previously-discovered transiting planets were known to be in the Kepler field: TrES–2 ( $\equiv$  Kepler–1), HAT–P–7 ( $\equiv$  Kepler–2), and HAT–P–11 ( $\equiv$  Kepler–3).

**Photometric accuracy** Photometric accuracies are 30–40 ppm for 12 mag stars with data binned in 6.5-h intervals (Gilliland et al., 2011a; Christiansen et al., 2012), a time interval benchmark roughly corresponding to the duration of an Earth–Sun transit viewed by a distant observer in the ecliptic plane. With several years of

data, Kepler is capable of detecting signals down to several ppm, depending on orbital period. Accuracies are  $\sim 700 \text{ ppm h}^{-1}$  over 11–16 mag (Jenkins et al., 2010b).

**Supporting surveys** Prior to launch, the stellar characteristics of all stars in the field with  $K_p < 14.5$  were determined (Koch et al., 2006), and numerous other ground-based surveys have been undertaken to support the mission (box, page 176).

### 6.6.3 K2 mission extension

Kepler's prime mission ended in 2013 May with the failure of a second attitude control reaction wheel. This prevented stable pointing away from the spacecraft's orbit plane, precluding further observations of its original target field. The modified 2-year funded *K2 mission*, the two-wheel operation mode, was designed to limit the effect of solar radiation pressure on spacecraft pointing, allowing the observation of selected fields along the ecliptic plane (Figure 6.11). Amongst them is a specific K2 microlensing campaign, campaign 9 (Henderson et al., 2016), with the expectation of discovering a few free-floating planets (Penny et al., 2017).

Operating in a 'step and stare' mode, for approximately 75-d campaigns, K2 again provides long-term, simultaneous optical observation of thousands of objects. The focus is on planets orbiting low-mass stars with  $P \lesssim 30 \text{ d}$ , filling the gap in duration and sensitivity between the Kepler and TESS missions, and providing pre-launch exoplanet target identification for JWST transit spectroscopy. Other scientific objectives include studies of young open clusters, bright stars, galaxies, supernovae, and asteroseismology.

Science commissioning demonstrated a photometric precision of 400 ppm in a 30-min observation, and a 6-h photometric precision of 80 ppm (both at  $V = 12$ ), within a factor of two of the main mission (Howell et al., 2014). A pointing drift, typically on a time scale of 6 h on which the spacecraft thrusters are fired, introduces significant systematic noise in the raw light curve (Vanderburg & Johnson, 2014; Armstrong et al., 2015a,b).

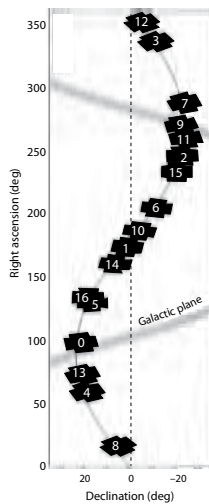
Methods to account for these systematic variability terms (including detrending, photometry, thresholding and detection) are being developed (Vanderburg & Johnson, 2014; Aigrain et al., 2015a; Baran et al., 2015a; Foreman-Mackey et al., 2015; Huang et al., 2015b; Lund et al., 2015b; Aigrain et al., 2016; Angus et al., 2016; Luger et al., 2016; Smith et al., 2016; Vanderburg et al., 2016c; Wang et al., 2016a).

**Results** The first K2 science observation run, campaign 1, began on 2014 May 30, with more than 20 discoveries by the end of 2015, around 100 by the end of 2016, and 155 by the end of 2017. A uniform treatment of the first year of K2 data yielded 234 candidates

**Supporting surveys for Kepler:** Various ground-based surveys have been undertaken to support the Kepler mission. These include, chronologically by publication date:

- KIC: to assist target selection, and the definition of optimal apertures for light curve extraction, ground-based imaging of the Kepler field was federated with various all-sky catalogues to create the Kepler Input Catalogue. KIC contains 13 million sources centred on the Kepler field, and includes broad-band photometry, Kepler magnitudes ( $K_p$ , defined via *gri* magnitudes), and stellar properties from model atmospheres (Brown et al., 2011b).
- BOKS (Burrell Optical Kepler Survey) was a pre-launch, 40-night time-series photometric campaign of a  $1.39 \text{ deg}^2$  area within the Kepler field, searching for transiting planets, with independent variability data. It has light curves of 54 687 stars (Feldmeier et al., 2011; Howell et al., 2010).
- KIS (Kepler-INT Survey) was a deep optical photometric survey complete to the Kepler confusion limit and covering  $116 \text{ deg}^2$  (Greiss et al., 2012).
- UBV survey to  $\sim 19$  mag, covering  $191 \text{ deg}^2$ , with 1.8 million sources detected in all 3 bands (Everett et al., 2012).
- DASCH (Digital Access to a Sky Century at Harvard) provides 100-year light curves, with 109 out of 997 Kepler host stars having  $\geq 100$  good measures (Tang et al., 2013).
- RATS-Kepler (Rapid Temporal Survey) was a deep high-cadence survey of the field, using the La Palma-INT and the Kitt Peak 1.3-m MDM telescope, employing the Kepler short-cadence (1-min) sampling, and finding more than 100 strongly variable sources (Ramsay et al., 2014).
- APOKASC, a joint asteroseismic-spectroscopic survey combining Kepler asteroseismology and APOGEE spectroscopy, providing  $T_{\text{eff}}$ ,  $[M/H]$ ,  $\log g$ ,  $M_*$ , and  $R_*$  for 1916 red giants (Pinsonneault et al., 2014) and 425 dwarfs and subgiants (Serenelli et al., 2017).
- a proper motion survey of KOI stars was compiled from first-moment centroids of single-season Kepler pixel data combined with positions and proper motions from UCAC4 and PPMXL, yielding precisions  $\sim 1 \text{ mas yr}^{-1}$ , suitable for stellar luminosity classification (Benedict et al., 2014).
- GALEX-CAUSE (Complete All-Sky UV Survey Extension) covers  $104 \text{ sq. deg.}$  of the Kepler field, yielding 669 928 near-ultraviolet sources, of which 475 164 are cross-matched with KIC. Some 327 of 451 confirmed Kepler exoplanet hosts, and 2614 of 4696 candidate hosts have near-ultraviolet photometry (Olmedo et al., 2015).
- KSwAGS is a joint Swift (X-ray) and ultraviolet survey of the Kepler field (Smith et al., 2015).
- mapping of the interstellar medium was made towards 17 early-type stars in the field (Johnson et al., 2015b). Related models of interstellar extinction derived from the KIC are given by Zasowski et al. (2015).
- California-Kepler Survey (CKS): high-resolution Keck-HIRES spectra for 1305 KOIs hosting 2075 transiting planets (Fulton et al., 2017; Johnson et al., 2017b; Petigura et al., 2017a, 2018b; Weiss et al., 2018).
- Mass estimates for 7000 KOIs (Chen & Kipping, 2018).
- APOGEE-ASCAP high-resolution multi-epoch spectral survey providing precise chemical abundances for 600 KOIs (Wilson et al., 2018).

In addition are various high-resolution imaging programmes to establish host star multiplicity (§7.9.3), including Robo-AO with its goal of targeting every Kepler planet candidate host star (Ziegler et al., 2017, and references).



Field	Dates	Comments
0	2014 Mar 08–2014 May 27	near Galactic anti-centre, M35, NGC 2158
1	2014 May 30–2014 Aug 21	north Galactic cap
2	2014 Aug 23–2014 Nov 13	near GC, M4, M80, M19, Upper Sco, $\rho$ Oph
3	2014 Nov 14–2015 Feb 03	south Galactic cap, Neptune
4	2015 Feb 07–2015 Apr 23	M45 (Pleiades), NGC 1647, Hyades
5	2015 Apr 27–2015 Jul 10	M44 (Beehive), M67
6	2015 Jul 14–2015 Sep 30	north Galactic cap
7	2015 Oct 04–2015 Dec 26	near GC, NGC 6717, Pluto
8	2016 Jan 03–2016 Mar 23	Uranus, IC 1613
9	2016 Apr 21–2016 Jul 01	GC, M21, M18, M25, M8, Earth, Mars
10	2016 Jul 06–2016 Sep 20	north Galactic cap
11	2016 Sep 24–2016 Dec 08	GC, Saturn
12	2016 Dec 15–2017 Mar 04	south Galactic cap, Chiron, Mars
13	2017 Mar 08–2017 May 27	Hyades, Taurus
14	2017 May 31–2017 Aug 19	north Galactic cap, Wolf 359, WASP-104
15	2017 Aug 23–2017 Nov 20	Upper Sco, GW Lib, HP Lib
16	2017 Dec 7–2018 Feb 25	galaxies, M44 (Beehive), M67, Earth

Figure 6.11: The survey fields (past and future) of the Kepler mission extension (K2) campaigns shown projected on the sky (left), and with observing dates and key targets (right; GC=Galactic centre, GAC=Galactic anti-centre). Each campaign has a duration of approximately 80 d, and remains fixed with a single boresight along the ecliptic plane. Campaign 9 included a focus on microlensing. From [keplerscience.arc.nasa.gov/k2-fields.html](http://keplerscience.arc.nasa.gov/k2-fields.html), 12 Nov 2016.

around 208 stars (Vanderburg et al., 2016c). A parallel analysis based on the CoRoT pipeline for the first 15 months (Campaigns 1–6) yielded 172 planetary candidates, along with 327 eclipsing binary candidates (Barros et al., 2016b).

Pipeline processing using the algorithm K2SC to model both K2 pointing systematics and stellar variability (Aigrain et al., 2016) detected 145 1-planet and 5 multi-planet systems from Campaigns 5–6, including previously-detected hot Jupiters (Pope et al., 2016).

In analogy with searches for ultra-short period planets in the Kepler data (§6.12.3), Adams et al. (2016) analysed data from Campaigns 0–5, and found 19 ultra-short period candidates with  $P < 1$  d, nine previously unreported, the shortest with  $P = 4.2$  h.

Candidates and follow-up optical spectroscopy for K2 Campaigns 5–8 are given by Petigura et al. (2018a).

After the nominal cut-off date for this review, Mayo et al. (2018) reported high-resolution spectroscopy for 275 candidates brighter than 13 mag observed during K2 Campaigns 0–10, securing a further 149 validated planets, K2–156 to K2–230 inclusive.

#### 6.6.4 Future follow-up for Kepler and K2

Observational follow-up of Kepler targets from the ground and space is underway on many fronts, and this section is intended to give a flavour of future prospects.

Improved models of stellar and instrumental noise, including temporally correlated noise, may enable the discovery of smaller, longer period planets, as well as improved characterisation of those already reported (Smith et al., 2012c; Stumpe et al., 2012). The majority

of Kepler planet masses being derived from transit time variations, more accurate transit times, longer temporal baselines, and more secure constraints on transit duration variations, will provide new or improved masses, and improved constraints on mutual orbit inclinations.

High-quality spectra of Kepler host stars will continue to refine their properties, and reduce the uncertainty in stellar parameters that often dominates the uncertainty in planetary properties. A spectrum can also determine the star's projected rotational velocity which, combined with the stellar spin period from Kepler photometry, constrains the angle between the stellar equator and planetary orbit (Hirano et al., 2014). Spectra and adaptive-optics imaging will contribute to the elimination of false-positives. Accurate host-star metallicities, which have already provided new insights into planet formation (Buchhave et al., 2012), will be expanded, amongst others, by LAMOST (Dong et al., 2014b).

**Gaia astrometry** Kepler stars are among the billion or more stars observed astrometrically by the Gaia mission. Gaia distances will improve knowledge of stellar parameters and, consequently, the planetary radii; better radii will in turn improve estimates of the planetary occurrence rates and compositions, and correlations between planetary and stellar properties.

For stars within  $\sim 200$  pc, including all Kepler hosts, Gaia should detect Jupiter analogues, revealing a more complete architecture for systems in which only the close-in planets are detectable by transits or radial velocity measurements (Perryman et al., 2014a).

**Space follow-up** The space-based all-sky surveys TESS (§6.8.1) and PLATO (§6.8.1) are expected to revisit

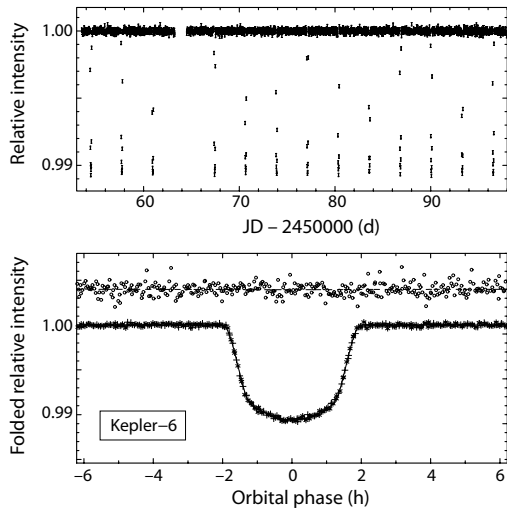


Figure 6.12: *Kepler-6b*. Top: detrended light curve. Bottom: photometry folded at the planet period, with the model fit to the transit (lower curve, left scale), and the best fit to the secondary eclipse (upper curve, right scale). Orbit parameters are  $P = 3.234723$  d,  $i = 86^\circ.8$  which, with radial velocity data, give  $M_p = 0.67M_J$ ,  $R_p = 1.32R_J$ ,  $\rho = 0.35 \text{ Mg m}^{-3}$ . From Dunham et al. (2010, Figure 1), by permission of IOP Publishing/AAS.

the Kepler field, providing a long temporal baseline that will yield improved occurrences, masses for longer period planets from transit time variations, and possibly a substantial number of transit duration variations.

Future missions to study known transiting planets include CHEOPS (§6.8.3), which will target known systems to discover additional transiting gas-poor planets, and JWST (§6.8.3), which will characterise the atmospheres of gas-poor planets and possibly break the degeneracy among several composition possibilities.

### 6.6.5 Synopsis of results

As of the end of 2017, Kepler-NNN identifiers had been assigned to 2315 *confirmed* transiting candidates (not counting K2). The NASA Exoplanet Archive lists a further 4496 unconfirmed transiting *candidates*.

A selection of specific Kepler systems of note is given in the box on page 179, and one example light curve, for Kepler-6 b, is shown in Figure 6.12. Others are presented in subsequent sections. A bibliography of all discoveries is given in Appendix D. A more detailed consideration of the Kepler results is included in Section 6.26, with other results described under specific sections, including transit time variations (§6.20), exomoons (§6.22), and co-planarity (§6.30.5).

### 6.6.6 Contributions to other fields

In addition to their exoplanet contributions, CoRoT and especially Kepler have made major contributions to the fields of asteroseismology more generally (§6.29.7), eclipsing binary stars, and other areas of stellar physics.

**Eclipsing binaries** The Kepler eclipsing binary catalogue contains some 3000 eclipsing binaries found from the entire Kepler data set. Catalogue compilation, including a derivation of the fit parameters, are described by Kirk et al. (2016a). Previous catalogue versions gave 1879 eclipsing binaries in the first data release (Prša et al., 2011), and 2165 in the second data release (Slawson et al., 2011). The online catalogue, searchable by KOI, KIC, and EPIC identifiers ([kepler.ebs.villanova.edu](http://kepler.ebs.villanova.edu)) gave 2604 eclipsing binaries in version 1 (2013 December 18), and 2878 in version 2 (2015 October 26).

Other eclipsing binaries are being included from the K2 extension (Conroy et al., 2014b; LaCourse et al., 2015).

There is a substantial literature on many aspects of Kepler eclipsing binaries, including mass transfer, triple systems, high-eccentricity orbits, and short-period systems, with many phenomena related to those of relevance to planetary systems, including limb darkening, beaming and ellipsoidal effects, eclipse timing, and Lidov-Kozai oscillations. Spectroscopic orbits of more than 100 eclipsing M dwarfs masquerading as transiting hot Jupiters are given by Triaud et al. (2017a).

**Non-discoveries** As emphasised by Lissauer et al. (2014a), transit surveys (including Kepler) have not yet found co-orbiting planets, viz. sharing the same average semi-major axis like the Trojan asteroids accompanying Jupiter, and Saturn's Janus and Epimetheus. Nor have they found exomoons, nor 'binary' planets orbiting one another (Kipping et al., 2012a, 2013b).

## 6.7 Other planet discoveries from space

**HST** SWEEPS (Sagittarius Window Eclipsing Extrasolar Planet Search) used HST-ACS (§6.10.2) to monitor 180 000 stars in the dense Sagittarius I window in the Galactic bulge, to look for transiting planets around F, G, K, and M dwarfs (Sahu et al., 2006). The survey resulted in two transit discoveries, SWEEPS-4 and SWEEPS-11.

**Spitzer** UCF-1.01 is the second planet ( $P = 1.4$  d) around GJ 436, discovered serendipitously by Spitzer (Stevenson et al., 2012b), and named after its discovery at the University of Central Florida.

## 6.8 Future observations from space

Future space observations will continue to exploit the benefits of uninterrupted observations from above the Earth's atmosphere (§6.1). One important focus is to enhance characterisation of transiting planets (both Doppler spectroscopy, and the detection of the reflected and radiated light from the planet and its atmosphere) by discovering more transiting planets orbiting *bright* stars, in contrast to the relatively faint systems from CoRoT and Kepler. For this, much wider field surveys are planned (Collier Cameron, 2016).

**Individual Kepler objects of note (many others could be mentioned, see Appendix D):**

**Kepler-9** two transiting giant planets with  $P = 19.2$  d and  $P = 38.9$  d (Holman et al., 2010; Dreizler & Ofir, 2014). The proximity to the 2:1 orbit resonance ( $38.91/19.24=2.02$ ) induces transit time variations of tens of minutes in both planets. This behaviour provides compelling confirmation of the reality of both planets, and provides estimates of their masses.

**Kepler-10** a 2-planet system, of which planet b is Kepler's first rocky planet (Batalha et al., 2011), with a very short orbital period ( $P = 20$  h). Its size and mass leads to a density  $\rho = 8.8 \pm 2 \text{ Mg m}^{-3}$ , consistent with an Earth-like composition.

**Kepler-11** a Sun-like star with six tightly-packed transiting planets ranging from  $1.8\text{--}4.2R_{\oplus}$  (Lissauer et al., 2011a; Migaszewski et al., 2012; Lissauer et al., 2013). Orbital periods of the inner five are between 10–47 d, with the period ratio between adjacent planets ranging from 1.26–1.74 (cf. solar system ratios between 1.63 for Venus–Earth, to 6.3 for Mars–Jupiter). The outermost, Kepler-11 g, has  $P = 118.4$  d. Transit time variations have been used to estimate masses. Most (if not all) have a substantial fraction of H and He, implying that H/He can dominate the volume of a planet that is only a few times Earth mass.

**Kepler-16** the first transiting circumbinary system (Doyle et al., 2011). Kepler-16 b is around Saturn's mass and radius ( $M_p = 106 \pm 5 M_{\oplus}$ ,  $R_p = 8.27 \pm 0.03 R_{\oplus}$ ), on a near circular orbit ( $e = 0.0069$ ) with  $P = 228.8$  d around an eclipsing binary with  $P_{\text{orb}} = 41$  d. The transits enable accurate measurements of the stellar masses and radii, with errors  $\leq 0.5\%$ . The primary's rotation axis is aligned with the binary's orbital axis to within  $2^\circ 4$  (Winn et al., 2011a). The planet will cease transiting one star in 2014, the second (brighter) star in 2018, and is thereafter non-transiting until 2042.

**Kepler-20** a 5-planet system, with planet e being the first smaller than Earth ( $R_p = 0.9 \pm 0.1 R_{\oplus}$ ) verified around another main-sequence star (Fressin et al., 2012b; Gautier et al., 2012). Its 6-day orbit implies a temperature too high to be habitable.

**Kepler-36** hosts two planets whose  $a$  differ by only 10% but whose compositions are dramatically different (Carter et al., 2012): rocky Kepler-36 b has  $M_p = 4.5 M_{\oplus}$ ,  $\rho = 7.46 \pm 0.7 \text{ Mg m}^{-3}$  and  $P = 13.8$  d, while Kepler-36 c has  $M_p = 8.7 M_{\oplus}$ ,  $\rho = 0.89 \pm 0.06 \text{ Mg m}^{-3}$  and  $P = 16.24$  d. Possibly the atmosphere of Kepler-36 b was stripped by photoevaporation or impact erosion, while Kepler-36 c retained its atmosphere because of its larger core mass and slightly larger  $a$  (Lopez & Fortney, 2013). Numerical integrations show that the configuration may be long-lived (Nagy & Ágas, 2013), although most nearby configurations are unstable on rather short time scales (Deck et al., 2012; Paardekooper et al., 2013; Quillen et al., 2013).

**Kepler-37** a 4-planet system, of which the innermost planet b, only slightly larger than Earth's Moon, with an orbital period of  $P = 13$  d, is the first planet smaller than Mercury to be found orbiting a main-sequence star (Barclay et al., 2013b). Due to its extremely small size and highly irradiated surface, it is most likely rocky with no atmosphere or water, similar to Mercury.

**Kepler-42** an M dwarf hosting three planets smaller than Earth (Muirhead et al., 2012b; Steffen & Farr, 2013).

**Kepler-62** a 5-planet system, of which planet f is the first known exoplanet whose radius ( $1.41 \pm 0.07 R_{\oplus}$ ) and semi-major axis suggest that it could be a rocky planet with stable liquid water at its surface (Borucki et al., 2013; Kaltenegger et al., 2013).

**Kepler-78** planet b has the shortest orbital period of any confirmed transiting exoplanet,  $P = 8.5$  h (Sanchis-Ojeda et al., 2013a). Slightly larger (and much hotter) than Earth, its mass, derived from radial velocity measures, implies a rocky composition (Howard et al., 2013; Pepe et al., 2013a).

**Kepler-88** 2-planet system, in which the transiting planet b has very large transit time variations of  $\sim 12$  h (Nesvorný et al., 2013a). This points to a non-transiting companion just wide of the 2:1 mean motion resonance, subsequently confirmed by radial velocity measurements (Barros et al., 2014b).

**Kepler-89** a 4-planet system (Weiss et al., 2013), in which two of the planets mutually occult, resulting in a planet–planet eclipse (Hirano et al., 2012a). The next double transit of this system will occur on 2026 April 1/2 (Masuda et al., 2013).

**Kepler-90** an 8-planet system, in which planets d, e, and f are super-Earths close to mean motion resonance chain (2:3:4), planets b and c (both  $< 2R_{\oplus}$ ) are within 0.5% of 4:5 mean motion resonance, and planets g and h are gas giants with exceptional transit time variations (25.7 h for planet g). A 3-planet system was identified by Batalha et al. (2013). A further 4 planets, and the system characterisation, was reported by Cabrera et al. (2014), and independently by Schmitt et al. (2014b), and the 8th by Shallue & Vanderburg (2018).

**Kepler-223** a 4-planet system in a chain of first-order resonances: periods are in the ratios 3:4:6:8 to within  $10^{-3}$  (Fabrycky et al., 2011; Moore et al., 2013).

**Kepler-413** a Neptune-size circumbinary planet. A slight misalignment between the planet and binary star orbital planes leads to orbital precession with a period of 11 yr, with stretches of hundreds of days in which the planet fails to transit the primary at inferior conjunction (Kostov et al., 2014). Possible Cassini states ( $\$6.30.4$ ) could lead to obliquity fluctuations of tens of degrees on the precession time scales.

**Kepler-421** a Uranus size planet, discovered from just two observed transits, with  $P = 704$  d, near the snow line, and the longest period of the Kepler transit discoveries (Kipping et al., 2014c).

**Kepler-444** a planetary system nearly as old as the Universe: a star 11.2 billion years old, with at least five Earth-sized planets. The tightly packed system is home to five small planets in very compact orbits (Campante et al., 2015).

**Kepler-1520 b**, widely referenced under its preliminary identifier KIC-12557548 (see  $\$6.14.22$ ), exhibits transits with depths varying by a factor 5, possibly due to an evaporating dusty atmosphere of a Mercury-like planet (Rappaport et al., 2012).

**KIC-8462852** was identified by the Planet Hunters project on the basis of its unusual transits, characterised by pronounced and irregular dimming up to 20%, lasting between 5–80 d (Boyajian et al., 2016). It is described further in Section 6.23.

Amongst ongoing or confirmed missions, two are dedicated to more efficient searches (TESS and PLATO). At least three (Gaia, Euclid, and WFIRST-AFTA) will perform significant surveys as by-products of their main objectives. Others will be either partly focused on (e.g. JWST and SPICA) or fully devoted to (e.g. CHEOPS and ARIEL) follow-up observations of known systems.

### 6.8.1 Approved surveys: dedicated

**TESS** NASA's Transiting Exoplanet Survey Satellite (TESS), led by MIT, will conduct a 2-yr transit search over the whole sky, targeting some 500 000 stars with  $V \leq 12$ . This contrasts with the majority of CoRoT and Kepler targets which, with their much smaller fields of view, have  $V \geq 12$ .

TESS is equipped with four wide-angle telescopes, each featuring a low-noise, low-power 16.8 Mpix MIT CCD, a  $24^\circ \times 24^\circ$  field of view, a 0.1-m effective pupil diameter, a lens assembly with seven optical elements, and a bandpass of 600–1000 nm. The survey is structured into 26 observation sectors, each sector being  $24^\circ \times 96^\circ$ , with sector overlap at the ecliptic poles to provide additional sensitivity toward smaller and longer-period exoplanets. Its highly elliptic 2:1 lunar resonant orbit ( $P/2$ ) provides unobstructed imaging of both north and south celestial hemispheres. The spacecraft will spend two 13.7-d orbits observing each sector, mapping the northern sky in year 1 and the southern sky in year 2. Each camera will take 2-min exposures focused on specifically targeted stars as part of its transit search, and 30-min full-frame exposures to search for other transient events (Ricker et al., 2015; Oelkers, 2017).

With a focus on nearby G and K stars, and including the nearest 1000–10 000 M dwarfs (Latham, 2008b), TESS is predicted to discover some 1700–3000 transiting candidates, some 300–500 of which are expected to be Earth-sized or a little larger, and some in the habitable zones (Ricker, 2014; Sullivan et al., 2015). The brightness of the host stars means that many of the discoveries will also be suitable for atmospheric studies with JWST and similar (Deming et al., 2009; Cowan et al., 2015; Placek et al., 2016; Quinn & White, 2016). Preparatory surveys include TESS-HERMES spectroscopy of 16 000 dwarfs and subgiants in the southern continuous viewing zone (Sharma et al., 2018). Advantages of joint TESS/CHEOPS observations (with different passbands) are assessed by Gaidos et al. (2017a).

TESS was one of three exoplanet proposals chosen for concept studies in 2011 September, and was selected in 2013 April. It was launched, on a SpaceX Falcon 9, on 2018 April 18.

**PLATO** ESA's PLATO (Planetary Transits and Oscillations of stars) aims to detect and characterise exoplanet transits of bright stars, for which efficient ground-based follow up is possible (Rauer et al., 2014, 2016). Building on CoRoT and Kepler, its emphasis is on bright targets ( $V < 11$ ), including very bright ( $V < 8$ ) and nearby stars. PLATO is expected to discover thousands of planets, with an emphasis on Earth- and super-Earth planets in the habitable zone. These will be preferentially accessible to PLATO compared to TESS because of PLATO's long uninterrupted observations (Marcos-Arenal et al., 2014; Hippke & Angerhausen, 2015b; Veras et al., 2015).

PLATO builds on two earlier ESA studies of a mission combining asteroseismology (the scientific driver in the early days)

and exoplanetary transits. The STARS proposal, with its 0.5 m<sup>2</sup> collecting area and 1°5 field, was not accepted (Schneider, 1996). A revised concept, Eddington (Favata, 2004), with an enlarged telescope of 1 m<sup>2</sup> collecting area and 6 deg<sup>2</sup> field of view, was accepted in 2000, but was subsequently cancelled. The original design concept for PLATO (Catala, 2009a,b) was also subsequently revised.

In its revised PLATO 2.0 form, it has 34 telescopes/cameras (32 with 25-s cadence, and 2 with 2.5-s cadence), providing a wide field (~2000 deg<sup>2</sup>, 20× Kepler), and large magnitude range (4–16 mag). It will be operated from the Lagrange point L2. Through parallel asteroseismology of 80 000 cool dwarfs with  $V < 11$  mag, it also aims to characterise  $R_p$  to some 2% (with  $R_p/R_\star$  from transits, and  $R_\star$  from Gaia and spectroscopy);  $M_p$  to some 10% (with  $M_p/M_\star$  from radial velocity follow-up, and  $M_\star$  from seismology); and stellar ages to ~10%.

The mission was submitted to ESA in 2011 as an unsuccessful candidate for the medium mission M2, re-submitted in 2013 January for the M3 competition, and selected for M3 in 2014 February. It is due for launch in 2026.

### 6.8.2 Approved surveys: by-products

**Gaia** The space astrometry mission Gaia, launched in 2013 (and ongoing as of early 2018), is expected to discover large numbers of planets as a result of their astrometric displacement, as detailed in Section 3.9. Various photometric transit detections are also expected, considered here under three categories: planets already known from other discovery techniques (notably radial velocity) with transits discoverable *a posteriori* in the Gaia photometric data; transiting planets discovered from the Gaia photometry alone; and Gaia astrometric discoveries subsequently found to transit (from Gaia or other photometry). The former will follow the sort of techniques used for the identification of known systems in the Hipparcos photometric data (§6.10.3). The latter are considered in Section 3.9.

Despite an accuracy of ~1 mmag per transit at  $G \leq 14$ –16 (Jordi et al., 2010), standard methods of searching parameter space for transits is poorly-suited to Gaia-like data sets with long time baselines and limited temporal coverage. An approach based on periodicities in high S/N outliers in the case of (nearly) Gaussian noise was proposed by Tingley (2011).

A directed follow-up strategy for discovering transits in low-cadence photometric surveys has been detailed for Hipparcos and Gaia (Dzigan & Zucker, 2011, 2012, 2013). Dzigan & Zucker (2012) took into account the scanning law, Galactic models, and detection limits to  $\leq 16$  mag, and concluded that the low cadence and relatively small number of measurements gives a limit on detectable orbit period of  $P \leq 10$  d, and a resulting number of expected discoveries from Gaia *photometry* of between one thousand and several thousand (Figure 6.13).

**Euclid** Although not formulated as an exoplanet-focused mission, Euclid (§5.9.5) is expected to contribute to exoplanet discoveries both through gravitational microlensing as well as via transits.



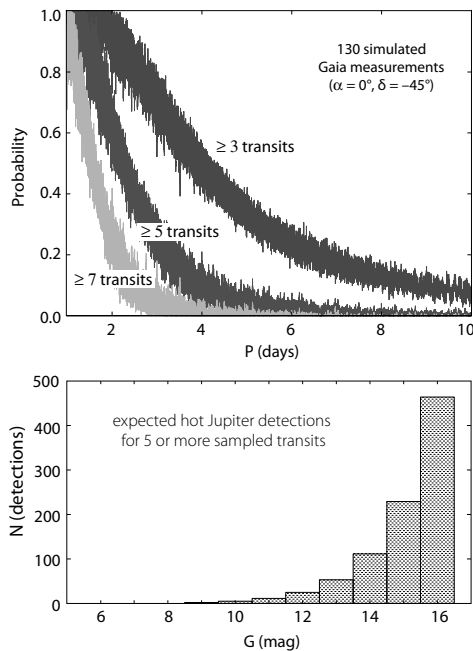


Figure 6.13: Photometric transit detection with Gaia. Top: sample observational window function for a sky area observed 130 times. Bottom: expected yield as a function of apparent magnitude, calculated for a minimum of five sampled transits, and a transit duration of 2 h. From Dzigan & Zucker (2012, Figures 2 and 3), by permission of IOP Publishing/AAS.

**WFIRST-AFTA** Although not primarily an exoplanet mission, WFIRST-AFTA (\$5.9.5) is expected to contribute to exoplanet discoveries both through gravitational microlensing (\$5.9.5), and via transits. Based on Kepler occurrence rates, WFIRST could detect 70 000 transiting planets with  $R \geq 2R_{\oplus}$  at  $d \leq 10$  kpc, a few thousand with full phase curves and measurable secondary eclipses, and with reflected light, Doppler beaming, ellipsoidal variations, and transit timing variations in a subset (Robinson et al., 2016; Montet et al., 2017b).

### 6.8.3 Future follow-up from space: approved

**CHEOPS** CHEOPS (CHAracterising ExOPlanets Satellite) will observe bright stars over the entire celestial sphere, but with the goal of detailed studies of known exoplanets (rather than the discovery of new ones) in the super-Earth to Neptune range ( $1 - 6R_{\oplus}$ ). It will follow up objects such as low-mass radial velocity discoveries which may transit, but where the signal-to-noise from the ground is inadequate to detect them (Yi et al., 2018).

Selected in 2012 October, it is a collaboration between ESA and the Swiss Space Agency, and is designated as the first S-class (small) mission in ESA's Cosmic Vision 2015–2025 programme. Covering  $0.4 - 1.1 \mu\text{m}$ , it comprises a single frame-transfer CCD in the focal plane of a 0.32-m diameter,  $f/5$  on-axis Ritchey–Chrétien

telescope. It will operate in a Sun-synchronous orbit of about 800 km altitude for a planned mission duration of 3.5 yr. It has a target launch date of late 2018.

The photometric precision is limited by stellar photon noise to  $150 \text{ ppm min}^{-1}$  at  $V = 9$  mag, corresponding to the detection of an Earth-sized planet transiting a  $0.9R_{\odot}$  host star with  $P = 60$  d detected at  $S/N > 10$ .

Detector stability requirements, at levels of  $2 \times 10^{-5}$ , have led to the development of an ultra-stable calibration light source (Wildi et al., 2015).

**JWST** The NASA/ESA James Webb Space Telescope, due for launch in mid-2020 with a nominal 5 yr mission, and a successor to HST and Spitzer, has a 6.5-m primary mirror, and will provide high signal-to-noise light curves and spectra of transiting planets. Imaging instruments NIRCam ( $0.6 - 5 \mu\text{m}$ ) and MIRI ( $5 - 28.5 \mu\text{m}$ ) should provide light curves of the primary and secondary eclipses of planets down to  $1M_{\oplus}$ , with filters, and the Tunable Filter Imager (TFI), providing limited spectral diagnostics. For spectroscopy, NIRCam ( $2.4 - 5 \mu\text{m}$ ), NIRSpec ( $1 - 5 \mu\text{m}$ ), and MIRI ( $5 - 29 \mu\text{m}$ ) provide a variety of wavelength coverage and resolution. Instrument configurations for exoplanet applications are tabulated by Clampin (2009), with exoplanet objectives variously described (Seager et al., 2009; Barstow et al., 2015; Greene et al., 2016; Mollière et al., 2017). The MIRI instrument is described in a series of 10 PASP papers in 2015, including an introduction to the instrument with an overview of exoplanet imaging and spectroscopy (Rieke et al., 2015), the low-resolution ( $R \sim 100$ ,  $5 - 12 \mu\text{m}$ ) spectrometer (Kendrew et al., 2015), the medium-resolution ( $R \sim 1300 - 3700$ ,  $5 - 28.5 \mu\text{m}$ ) spectrometer (Wells et al., 2015), and the coronagraphs (Boccaletti et al., 2015).

JWST should detect  $\text{H}_2\text{O}$ ,  $\text{CH}_4$ , and  $\text{CO}$  in gas giants, while hydrogen sulphide and  $\text{PH}_3$  may be detectable (Wang et al., 2017a). It should characterise planets discovered by TESS and, depending on operational lifetime, PLATO. Targets for 'early release science' (Stevenson, 2016) are assessed through the HST Panchromatic Comparative Exoplanet Treasury (PanCET) programme. Candidates include WASP-62 (Stevenson et al., 2016b) and WASP-101 (Wakeford et al., 2017b). Various tools have been made available: for the selection of observing modes (Batalha & Line, 2017), for optimising phase curve observations (Placek et al., 2017), and for estimating observational noise (Batalha et al., 2017b; Howe et al., 2017).

**CUTE** The Colorado Ultraviolet Transit Experiment is a 6-unit CubeSat, using near-ultraviolet transmission spectroscopy ( $255 - 330 \text{ nm}$ ) to characterise atmospheric composition and mass-loss rates. Plans are for a 1-year mission, and a launch in 2020 (Fleming et al., 2017).

**ARIEL** A revision of EChO, ARIEL was one of three candidates for the ESA medium class mission M4, selected in 2018 March with launch in the late 2020s (Puig et al., 2016). It will undertake infrared spectroscopy of some 500 known transiting planets, over 3.5-yr operations from an L2 orbit. It employs a 1-m telescope, an

infrared spectrometer covering 1.95–7.8  $\mu\text{m}$ , and photometric bands in the visible and near-infrared to measure stellar activity, albedo, and clouds. Targets extend down to super-Earth and Earth-size in a variety of environments, with the main focus being hot and temperate planets in close-in orbits (Encrenaz et al., 2017).

#### 6.8.4 Future follow-up from space: candidates

A number of other space mission have been proposed for dedicated follow-up observations.

##### Under consideration

- *SPICA*: the Japanese-led ‘Space Infra-Red Telescope for Cosmology and Astrophysics’ is a proposed 3.5-m mid- to far-infrared (3.5–200  $\mu\text{m}$ ) mission (Goicoechea et al., 2008; Nakagawa et al., 2015). Mechanical cryocoolers cool the mirror to 4.5 K (cf. 80 K of Herschel) providing improved sensitivity at 10–100  $\mu\text{m}$ . Instruments include a 30–200  $\mu\text{m}$  imaging spectrometer (SAFARI, Goicoechea & Swinyard, 2010), a 4–40  $\mu\text{m}$  high-resolution spectrograph, a 10–100  $\mu\text{m}$  low-resolution spectrograph, and a 5–20  $\mu\text{m}$  imaging coronagraph. Exoplanet coronagraphic imaging has been assessed by Enya et al. (2011a,b). The launch target is currently 2027–28 (Nakagawa et al., 2017).

##### Proposed but discontinued

- *EChO*: a proposed ESA mission for the characterisation of transiting planet atmospheres (Tessenyi et al., 2012; Eccleston et al., 2015; Tinetti et al., 2015). It competed unsuccessfully for ESA’s medium mission M3 in 2014, and was re-formulated as ARIEL (\$6.8.4). A collection of 26 papers covered all aspects of the mission (Tinetti & Drossart, 2015).
- *EXOPLANET-SAT*: a proposed low-cost CubeSat platform for detecting transiting Earths in the habitable zone of the brightest Sun-like stars (Knapp et al., 2011; Jensen-Clem et al., 2011).
- *FINESSE*: the ‘Fast INfrared Exoplanet Spectroscopy Survey Explorer’ targeted transmission spectra of 200 planets over a 2-yr lifetime (Swain, 2012a,b). It was among three exoplanet proposals selected for concept studies by NASA in 2011 September.
- *Occulting Ozone Observatory*: a 1–2-m telescope with a free-flying occulter, with four filters each in the 250–550 nm and 500–1100 nm bands. Objectives included detection of atmospheric  $\text{O}_3$  in Earth-like planets and  $\text{CH}_4$  in gas giants (Pravdo et al., 2010; Savransky et al., 2010b).
- *SPICES*: the ‘Spectro-Polarimetric Imaging and Characterisation of Exoplanetary Systems’ mission was a 1.5-m coronagraphic telescope, derived from TPF and an evolution of SEE-COAST (Schneider et al., 2009b; Galicher et al., 2010a; Boccaletti et al., 2012; Maire et al., 2012a) aiming to image and characterise nearby long-period (0.5–10 au) planets and circumstellar disks in the visible (450–900 nm) at  $R \sim 40$ .
- *THESIS*: was a NASA MIDEX proposal for exoplanet spectroscopy (Swain et al., 2009a, 2010b; Deroo et al., 2010). It comprised a 1.4-m primary mirror, and an  $R = 2000$  spectrometer providing spectra from 2–14  $\mu\text{m}$ .
- *TRACER*: the ‘Transit Characterisation Explorer’ was another concept to characterise transiting planets (Clampin, 2008).

## 6.9 Follow-up observations from the ground

This section does not list all telescopes which have been used for transit/eclipse photometric/spectroscopic fol-

low up, but provides an incomplete selection of some specific facilities and ‘networks’.

**Scheduling** Routines to predict which periodic events will be visible from a given location on a given date have been developed for the follow-up of transit observations. For example, TAPIR has been developed for the KELT programme ([astro.swarthmore.edu/~jensen/tapir.html](http://astro.swarthmore.edu/~jensen/tapir.html)), with a similar www interface provided by the Exoplanet Transit Database ([var2.astro.cz/ETD/predictions.php](http://var2.astro.cz/ETD/predictions.php)).

### 6.9.1 Transit photometry

Various robotic systems are being employed.

- *DEMONEX*: the ‘DEdicated MONitor of EXotransits’ is a 0.5-m robotic telescope which aims to monitor bright host stars to provide a homogeneous data set of precise relative photometry for all systems visible from its location at Winer Observatory in Sonoita, Arizona (Eastman et al., 2010a).
- *ExTrA*: ‘Exoplanets in Transit and their Atmospheres’ (Grenoble) is an ERC-funded instrument at La Silla, which adds spectroscopy to standard differential transit photometry (Bonfils et al., 2015). It comprises a near-infrared fiber-fed multi-object spectrograph ( $R > 200$ , 0.8–1.6  $\mu\text{m}$ ) fed by three 0.6-m telescopes. ExTrA aims to find transiting habitable exo-Earths around bright nearby M dwarfs, either as an independent survey, or by follow-up of candidates identified by K2 and TESS.
- *LDSS-3*: the Magellan Low Dispersion Survey Spectrograph 3 provides improved sensitivity and fringing in the red optical, and has been used in searches for the spectroscopic signature of  $\text{H}_2\text{O}$ , e.g. for HAT-P-26 b (Stevenson et al., 2016a).
- *MASTER*: the MASTER-II robotic network was developed to study optical emission of  $\gamma$ -ray bursts (Gorbovskey et al., 2013). Burdanov et al. (2013) reported two transiting candidates in Cygnus, MASTER-1 b ( $P = 0.85$  d,  $R = 12.4$ ,  $\Delta F = 0.015$  mag) and MASTER-2 b ( $P = 0.98$  d,  $R = 13.8$ ,  $\Delta F = 0.017$  mag). Further results are reported by Burdanov et al. (2016).
- *MuSCAT*: the Multicolour Simultaneous Camera for studying Atmospheres of Transiting exoplanets, is a simultaneous 3-colour imaging system at the Okayama 1.88-m telescope (Narita et al., 2015a; Fukui et al., 2016b).
- *NITES*: the ‘Near Infra-red Transiting Exoplanets’ telescope is a semi-robotic 0.4-m ( $f/10$ ) telescope with an 11  $\text{armin}^2$  field, installed at ORM, La Palma (McCormac et al., 2014). Observations include photometric monitoring of M71 (McCormac et al., 2014), and K2-19 (Armstrong et al., 2015b).
- *PEST*: the ‘Perth Exoplanet Survey Telescope’ is an amateur 12-inch observatory in Australia, which has contributed to a number of transit and microlensing planet discoveries.

### 6.9.2 High time resolution

The need for accurate transit time measurements has brought a renewed focus to instrumental techniques.

- *MORIS*: the ‘MIT Optical Rapid Imaging System’ is a high-speed visible imager at the 3-m IRTF, Mauna Kea (Hawaii). It has a  $60 \times 60$  arcsec<sup>2</sup> field, and readout rates of 3.5–35 Hz. Observations include XO-2 b, with a photometric precision of 0.5 mmag in 2 min and a mid-transit precision of 23 s (Gulbis et al., 2011), and CoRoT-1 b (Schlawin et al., 2014).

- *Orthogonal transfer CCDs*: these shift accumulated charge both horizontally and vertically during an exposure to produce broad, stable point-spread functions. Observations of WASP-10 and TrES-3 with a photometric precision of 0.7 mmag per minute have been reported by Johnson et al. (2009b).
- *RISE*: the ‘Rapid Imager to Search for Exoplanets’ is a fast CCD imager at the 2-m Liverpool Telescope, La Palma (Steele et al., 2008). Mid-transit accuracies reach  $\sim 10$  s in the best cases (Steele et al., 2008; Gibson et al., 2010b). Transit studies include WASP-3 (Gibson et al., 2008), TrES-3 (Gibson et al., 2009), HAT-P-3 (Gibson et al., 2010b), and WASP-13 (Barros et al., 2012).
- *ULTRACAM*: a multicolour photometer employing 2 dichroic splitters and 3 frame-transfer CCD cameras providing 3-colour imaging at up to 500 Hz, although the 5 arcmin field limits the probability of a comparison star of suitable brightness (Dhillon et al., 2007; Bentley et al., 2009). It has been used for exoplanet observations on the 4.2-m WHT (La Palma), the 8.2-m ESO-VLT, and the 3.5-m NTT (CHL), e.g. for WASP-12 (Föhring et al., 2013), and WASP-17 (Figure 6.7, Bento et al., 2014).
- *SCAM (STJ)*: the possibility of measuring the energy of an individual optical photon directly, using superconducting tunnel junctions (STJ), and without recourse to filters or dispersive devices, was first proposed theoretically by Perryman et al. (1993), and demonstrated by Peacock et al. (1996). Other similar technological implementations have since been developed (e.g. Cabrera et al., 1998; Mazin et al., 2013; Eisenhauer & Raab, 2015). These devices have very high quantum efficiency, approaching 100% from the ultraviolet to the near infrared, along with  $\mu$ s-level arrival time and spatial position of each photon (e.g. Perryman et al., 1999; de Bruijne et al., 2002; Reynolds et al., 2003). SCAM (STJ-based) transit observations of HD 189733, HD 209458, and TrES-1, using a  $12 \times 10$  superconducting pixel array, were reported by Stankov et al. (2007). The  $2 \mu$ m interpixel gaps lead to a variable seeing-induced photometric light loss which limits current applications.

### 6.9.3 Interferometric observations

Interferometric observations can provide a direct measurement of stellar angular diameters  $\theta_\star$ , which can then be transformed into  $R_\star$  on the basis of a trigonometric parallax, independently of stellar evolution models. For example, CHARA angular diameter measurements of 24 planet hosting stars (mostly non-transiting) are given by Baines et al. (2008).

Of the transiting planets, the star with the largest angular diameter is HD 189733 with  $\theta_\star = 376 \pm 31 \mu$ as determined using the CHARA array (Baines et al., 2007). The angular diameters of GJ 436, HD 149026, and HD 209458 are also in the range 170–250  $\mu$ as.

**Transit position angle** Uniquely, interferometers like CHARA or VLTI can directly determine the position angle of the planet’s orbital plane, because of the asymmetry in the source brightness introduced by the transiting planet (van Belle, 2008).  $R_p$  and  $b$  are measurement by-products which provide independent constraints on these parameters.

At any instant, an interferometer measures one Fourier component of the source’s brightness distribution. In aperture synthesis, the overall source structure is then reconstructed from the different telescope combinations, whose projected baseline separations also vary as the Earth rotates.

Ignoring the absolute phase term, the complex interferometric visibility of a transiting star–planet system is given by (van Belle, 2008, eqn 2)

$$V = \frac{V_\star + r V_p e^{-2\pi i \mathbf{B} \cdot \Delta \mathbf{s} / \lambda}}{1 + r}, \quad (6.3)$$

where  $V_\star$ ,  $V_p$  are the visibility functions of the star and planet,  $V = 2J_1(x)/x$ , where  $J_1$  is the Bessel function,  $x = \theta_{\text{ud}} \pi B / \lambda$ ,  $\theta_{\text{ud}}$  the angular diameters of the relevant uniform disks,  $\lambda$  the observing wavelength,  $\mathbf{B}$  and  $\mathbf{s}$  are the baseline and relative separation vectors, and the brightness ratio  $r = -(R_p / R_\star)^2$ .

In practice, visibility phases are corrupted by atmospheric turbulence. But for three or more telescopes, the closure phase  $\Phi$ , given by the sum of the visibility phases around a closed loop of baselines, and long used in radio astronomy, cancels many of the atmospheric and instrument effects, and provides a highly sensitive probe for interferometric image reconstruction (Pearson & Readhead, 1984; Monnier, 2007).

The CHARA interferometer consists of six 1-m telescopes in a Y-configuration, with two telescopes per arm, and with the three longest baselines  $B > 300$  m. The Michigan Infrared Combiner (MIRC) instrument combines currently four (and potentially six) telescopes simultaneously, providing three (and potentially 10) independent closure phase measurements with a precision of  $\sigma_\Phi \approx 0.03$  (Monnier et al., 2006). Preliminary studies on  $\nu$  And were reported by Zhao et al. (2008). VLTI-AMBER can also determine closure phases, but at a somewhat lower accuracy level of a few degrees (Weigelt et al., 2007).

Beyond AMBER, VLTI-PIONIER (Precision Integrated-Optics Near-infrared Imaging Experiment) is a 4-beam H-band interferometer with more stable ‘integrated optics on a chip’ (Le Bouquin et al., 2011). It has been operational since late 2010, and is a precursor for the interferometric instruments VSI and GRAVITY. It combines beams either from the 8.2-m Unit Telescopes, or from the 1.8-m Auxiliary Telescopes to provide 6-baseline visibilities and four closure phases simultaneously. Exoplanet applications to date include resolving circumstellar material around  $\beta$  Pic (Defrère et al., 2012), excluding close stars in exozodiacal surveys (Marion et al., 2014), and characterising debris disks (Ertel et al., 2014).

Figure 6.14 illustrates the dimensions for HD 189733, and shows how the transit geometry affects the complex visibilities, and more particularly the closure phases. Interferometric closure phases should provide an important probe of the transit geometry in the future, particularly valuable for higher-order transit light curve effects.

Imaging based on intensity interferometry, for example with the Cherenkov Telescope Array (CTA), is considered further in Section 7.8.1.

### 6.9.4 Follow-up from ground: networks

These are collaborative programmes generally with some specific scientific objective. Those listed here are not necessarily large, the most significant, or the most productive, but included as a reference to some of the associated acronyms found in the literature.

- *APOSTLE*: the ‘Apache Point Observatory Survey of Transit Light curves of Exoplanets’ uses the ARC 3.5-m telescope at Apache Point, New Mexico, with high-speed CCD photometry. Follow-up transit observations include GJ 1214 b (Kundurthy et al., 2011), TrES-3 b (Kundurthy et al., 2013b), WASP-2 b (Becker et al., 2013), and XO-2 b (Kundurthy et al., 2013a).

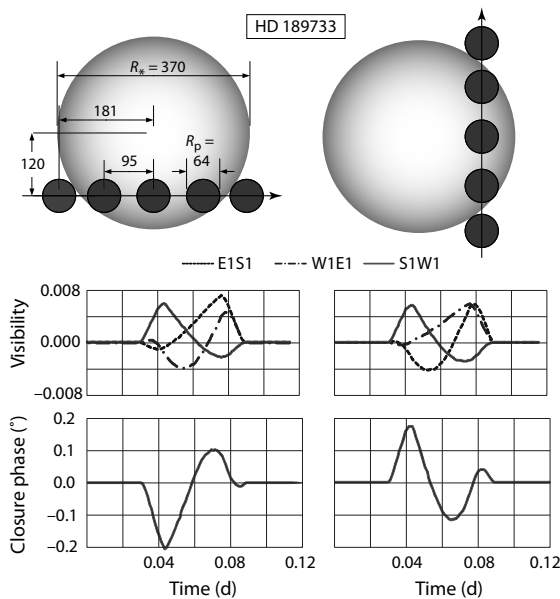


Figure 6.14: Simulated interferometric observations of HD 189733. The figure shows two different possible transit geometries (top), the corresponding expected visibility amplitude for each of three CHARA baselines (middle), and the visibility phase for the array's S1W1 baseline (bottom). In the top panels, the dimensions are the angles in microarcsec inferred for the system from the discovery parameters (Bouchy et al., 2005c). From van Belle (2008, Figure 2), reproduced by permission, Institute of Physics Publishing.

- **GROUSE**: the 'GROUND-based Secondary Eclipse' project uses ground-based telescopes for exoplanet secondary eclipse observations in the optical and near-infrared (de Mooij & Snellen, 2009; de Mooij et al., 2011, 2013b).
- **TASTE**: the 'Asiago Search for Transit timing variations of Exoplanets' programme targets systems with the primary goal of detecting transit timing variations (Nascimbeni et al., 2011a,b, 2013a; Granata et al., 2014).
- **TERMS**: the 'Transit Ephemeris Refinement and Monitoring Survey' programme aims to address the bias of transit detections to short period planets (simply due to the geometric transit probability, §6.3.1) through photometric monitoring of known radial velocity planets at times of predicted possible transits (Kane, 2007; Kane & von Braun, 2008; Kane et al., 2009; Dragomir et al., 2011). Results include HD 168443 (Pilyavsky et al., 2011), HD 114762 (Kane et al., 2011c), HD 156846 (Kane et al., 2011d), HD 192263 (Dragomir et al., 2012a), HD 37605 (Wang et al., 2012c), HD 38529 (Henry et al., 2013).
- **TraMoS**: the 'Transit Monitoring in the South' project aims at homogeneous transit monitoring in the southern hemisphere, using the SMARTS 1-m at CTIO, and the SOAR Optical Imager (SOI) 4.2-m at Cerro Pachón (Hoyer et al., 2011, 2012, 2013).
- **Transit light curve project**: the collaboration aims to acquire transit data for known systems (Holman et al., 2006; Winn et al., 2007b,d; Holman et al., 2007a; Winn et al., 2007c; Holman et al., 2007b; Winn et al., 2007a, 2008c,d, 2009b,a; Fernandez et al., 2009; Carter et al., 2011c; Chan et al., 2011).

## 6.10 Follow-up observations from space

The Hubble Space Telescope (HST) and Spitzer Space Telescope have provided high signal-to-noise observations of light curves and spectra of transiting exoplanets, yielding detailed characterisation of several transiting systems discovered from the ground. They are described only briefly in this section, with results summarised in §6.24. Hipparcos and MOST have made other contributions to the observations of planetary transits.

### 6.10.1 EPOXI-EPOCH

NASA's Deep Impact mission was launched in 2005 January. After its fly-by of comet Tempel 1, it was re-oriented in 2008 (and renamed EPOXI) for the fly-by of comet Hartley 2. Before the Hartley 2 fly-by, the satellite was reconfigured to make two distinct observations relevant to exoplanets, an experiment referred to as EPOCH (Extrasolar Planet Observation and Characterisation). The mission was suspended after contact with the spacecraft was lost in 2013 August.

Between 2008 January–August, using its larger (aberrated) telescope, the 0.3-m High Resolution Instrument, EPOXI-EPOCH observed transits of seven exoplanets, each observed continuously for several weeks (Ballard et al., 2008, 2011a): XO-2 (Ballard et al., 2009), GJ 436 (Ballard et al., 2010b); HAT-P-7 (Christiansen et al., 2010); and HAT-P-4, TrES-2, TrES-3, and WASP-3 (Christiansen et al., 2011).

EPOXI-EPOCH also observed the Earth's disk, at 0.18 au and  $57^\circ$  phase angle, and at 0.34 au and  $77^\circ$  phase angle in 2008 June (Crow et al., 2011; Robinson et al., 2011; Livengood et al., 2011; Cowan & Strait, 2013). Observations with various filters and time sampling over a range of wavelengths from 350 nm to  $4.8 \mu\text{m}$ , provided data intended as a template for characterising Earth-type exoplanets. Its infrared spectroscopy shows the signatures of  $\text{H}_2\text{O}$  and  $\text{CO}_2$ , demonstrates significant time-variability of the optical spectrum associated with various terrestrial phenomena, and quantifies the suitability of the 'red edge' as a signature of chlorophyll-based life.

### 6.10.2 Hubble Space Telescope

Launched in 1990, the 2.4-m NASA/ESA Hubble Space Telescope has been used for the SWEEPS transit survey, and to observe numerous known transit events, providing high-quality transit light curves, and various atmospheric diagnostics.

**HST-SWEEPS** SWEEPS (Sagittarius Window Eclipsing Extrasolar Planet Search) used HST-ACS to monitor 180 000 stars in the Sagittarius I window in the Galactic bulge, to look for transiting planets around F, G, K, and M dwarfs (Sahu et al., 2006). From a 7-d survey in 2004 February, they discovered 16 candidates with periods of 0.6–4.2 d. Radial velocity observations of the two brightest ( $V \sim 19$  mag) confirmed the planetary nature of SWEEPS-4 and SWEEPS-11.

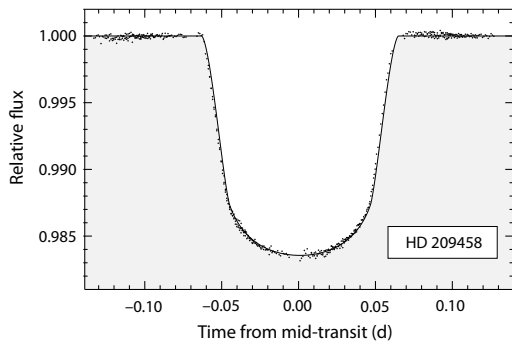


Figure 6.15: HD 209458, observed over four transits with the HST Imaging Spectrograph, and co-phased assuming a period  $P = 3.52474$  d. The quality may be compared with the (ground-based) discovery light curve (Figure 6.1). From Brown et al. (2001, Figure 3), by permission of IOP Publishing/AAS.

**Transits and atmospheres** HST instruments have been used to study transits, secondary eclipses, and full phase curves of known transiting systems (§11.6): the Space Telescope Imaging Spectrograph (STIS, installed in 1997, failed in 2004, and replaced in May 2009), the Near Infrared Camera and Multi-Object Spectrometer (NICMOS, operational 1997–1999 and 2002–2008, largely replaced by WFC3), the Advanced Camera for Surveys (ACS, installed in 2002, with reduced functionality after 2006), the Cosmic Origins Spectrograph (COS, installed in 2009), and the Wide Field Camera 3 (WFC3, installed in 2009), for which instrument models have been successively improved (Zhou et al., 2017b).

Results include high signal-to-noise STIS observation of HD 209458 (Figure 6.15), with the light dispersed over many pixels (Brown et al., 2001). ACS observations of three transits of HD 189733 resulted in a signal-to-noise of 15 000 on individual measurements, and 35 000 over 10-min averages (Pont et al., 2007a). Other observations include the first detection of an atomic species in an exoplanet atmosphere, Na in HD 209458 b (Charbonneau et al., 2002), and the detection of atomic H (Vidal-Madjar et al., 2003), Mg (Vidal-Madjar et al., 2013), and O<sub>2</sub> in HD 189733 b (Ben-Jaffel & Ballester, 2013).

At infrared wavelengths, molecular CO, CO<sub>2</sub>, H<sub>2</sub>O and CH<sub>4</sub>, as observed in the giant planets in the solar system, have been reported in the atmospheres of HD 209458 b (Swain et al., 2009b) and HD 189733 b (Swain et al., 2008b), although details depend on the instrumental models (Gibson et al., 2011b). Between 0.550–1.050  $\mu\text{m}$ , for example, HD 189733 b has a featureless spectrum, with slope consistent with Rayleigh scattering from clouds or haze in the planet’s upper atmosphere. Flat featureless atmospheric spectra at 1–1.7  $\mu\text{m}$  in the case of GJ 436 b (Knutson et al., 2014a) and GJ 1214 b (Kreidberg et al., 2014b) suggest that this may be a common feature of Neptune-mass and super-Earth mass planets, ruling out a H-rich atmosphere.

The HST Panchromatic Comparative Exoplanet Treasury (PanCET) programme has been established partly in preparation for prioritising JWST observations (§6.8.3), of which WASP-101 was the first target (Wakeford et al., 2017b).

**Spatial scanning** Spatial scanning under Fine Guidance Sensor (FGS) control was developed for the WFC3 instrument in 2011. In this mode, the target field is observed while the telescope is slewing in a user-defined direction and rate. The objective is to collect of order  $10^8$  photons or more per source without saturation, thus allowing high-precision global and time-resolved photometry of bright sources including transiting systems (McCullough et al., 2012, 2014b; Riess et al., 2014).

### 6.10.3 Hipparcos

While primarily an astrometric mission, the broad optical pass band of Hipparcos, combined with the 100 or so distinct measurement epochs between 1990–93 for 118 000 stars, provides a well-calibrated multi-epoch global system of high-accuracy photometric measurements. This has led to the ‘precovery’ (pre-discovery recovery) of at least five transiting planets.

Once photometric transits had been reported for HD 209458 by Charbonneau et al. (2000) and Henry et al. (2000), the period transit signal was discovered *a posteriori* in the Hipparcos epoch photometry data (Söderhjelm et al., 1999; Robichon & Arenou, 2000). Hipparcos observed the star on 89 occasions, of which five corresponded to planetary transits (Figure 6.16a–b). The orbital period of about 3.5 d, and a transit duration of about 0.1 d, imply a 3% probability of observing a transit at any given epoch. The Hipparcos median magnitude is  $H_p = 7.7719 \pm 0.002$ , and the transits resulted in a  $2.3 \pm 0.4\%$  mean decrease in flux. From the temporal baseline of more than eight years, or nearly 1000 periods, between the Hipparcos observations in the early 1990s and the first ground-based detection in the late 1990s, the period was improved 20-fold, from 3.524 47 d determined on ground (Mazeh et al., 2000) to 3.524 739(14) d when combined with the Hipparcos data (Robichon & Arenou, 2000; Castellano et al., 2000).

The second transiting star bright enough to appear in the Hipparcos catalogue, HD 149026, has not been detected in the Hipparcos photometric data.

Bouchy et al. (2005c) and Hébrard & Lecavelier des Etangs (2006) both reported transits for the ninth transiting planet to be discovered, and the third bright enough to be in the catalogue, HD 189733. It has  $P = 2.219$  d, a transit depth of around 3%, and a transit duration of around 1.6 h. Hébrard & Lecavelier des Etangs (2006) showed that around 3% of randomly chosen observations would be expected to fall during a transit, such that out of the 176 available Hipparcos observations, some five corresponding to transit periods would

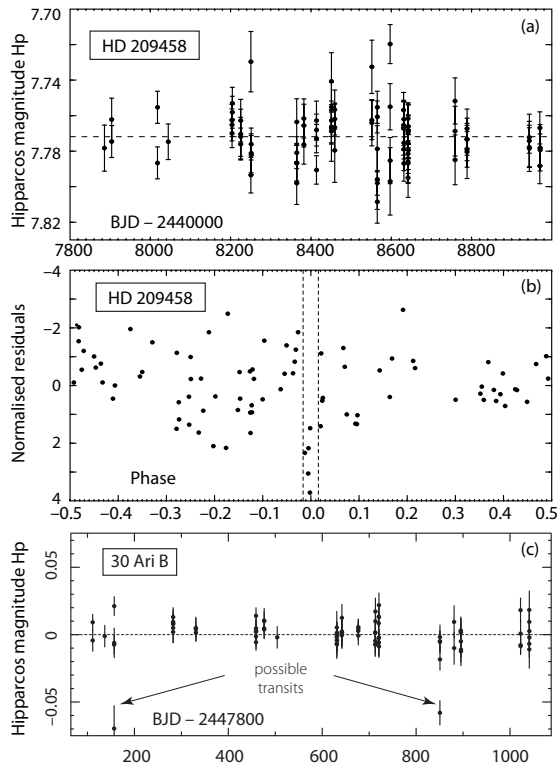


Figure 6.16: *Hipparcos* photometry of two systems in which transits can be recognised once the orbit period is known. Top two: HD 209458 showing (a) photometry over the 3.4-yr mission, and (b) normalised residuals as a function of the planet’s orbital phase. Vertical dashed lines show the nominal transit duration. From Robichon & Arenou (2000, Figures 1 and 3), reproduced with permission © ESO. (c) 30 Ari B over the 3.4-yr mission. Standard errors are  $\sim 0.01$  mag. Two significant outliers, indicating a 5% reduction in brightness, are separated by  $\sim 693.8$  d, roughly twice the planet’s orbital period. From Kane et al. (2015a, Figure 5), by permission of IOP Publishing/AAS.

be expected. Folding of the *Hipparcos* light curve indeed shows that such a number of data points fall at the time of transits. The combination of *Hipparcos* and the ground-based observations of Bouchy et al. (2005c) span a period of 15 years, from which  $P = 2.218574(8)$  d, with a resulting accuracy in the orbital period of  $\sim 1$  s.

30 Ari B b has also been considered as a provisionally transiting discovery from *Hipparcos* photometry (Kane et al., 2015a, see Figure 6.16c). McDonald & Kerins (2018) identified pre-discovery transits for WASP-18 and WASP-33, and possibly for HAT-P-2 and HAT-P-56.

**Other searches** Other transit events probably remain buried in the *Hipparcos* epoch photometry database, although they are problematic to identify because of the large and unconstrained search space, and the complexity of dealing with the resulting large number of false-positives. Hébrard et al. (2006) systematically searched for periods compatible with known planet transits, and constructed a ranked list for follow-up measurements; 194 observed with HARPS revealed only active stars.

Koen & Lombard (2002) described procedures for identifying transit events in photometric time series, applying them to 10 820 bright ( $H_p < 7$  mag) non-variable *Hipparcos* stars. Laughlin (2000) defined a sample of 206 metal-rich stars of spectral type FGK which have an enhanced probability of harbouring short-period planets, and searched for *Hipparcos* transits: various candidate transit periods were identified. Jenkins et al. (2002) presented empirical methods for setting detection thresholds and for establishing confidence levels, applicable to the sparse *Hipparcos* data.

A corresponding, but improved analysis should also be possible from the *Gaia* photometric time series (Robichon, 2002; Eyer & Mignard, 2005).

#### 6.10.4 MOST

The Canadian MOST satellite (Microvariability and Oscillations of Stars) was a precursor of CoRoT, designed for studies of stellar oscillations but with applicability to parallel planetary transit studies. Canada’s first space telescope (and first science satellite since *ISIS II*), it was funded by the Canadian Space Agency until 2014, with ground-based and scientific support from Austria. Launched on 2003 June 30, it comprises a 0.15-m telescope feeding two CCDs (for attitude tracking and science), with a single 300 nm wide filter centred at 525 nm. The polar Sun-synchronous low-Earth orbit allows stars between  $-19^\circ < \delta < +36^\circ$  to be observed continuously for up to 60 d (Walker et al., 2003a).

Observations of HD 209458 over 14 d in 2004 and 44 d in 2005 placed upper limits on the planet albedo, ruling out bright reflective clouds in its atmosphere (Rowe et al., 2006, 2008), revealing no other transit periods (Croll et al., 2007a), placing upper limits on transit time variations (Miller-Ricci et al., 2008b), and placing constraints on Trojan asteroids (Moldovan et al., 2010). Absence of transit time variations for HD 189733 excluded super-Earths in orbital resonance (Croll et al., 2007b; Miller-Ricci et al., 2008a), and provided constraints on stellar variability (Lanza et al., 2011a). Observations of  $\tau$  Boo detected stellar variability possibly induced by its planetary companion (Walker et al., 2008).

Observations since 2010 included: 55 Cnc e (Winn et al., 2011c; Dragomir et al., 2014); GJ 581 (Dragomir et al., 2012c); HD 80606 (Roberts et al., 2013a); and HD 97658 (Dragomir et al., 2012b, 2013).

#### 6.10.5 Spitzer Space Telescope

NASA’s *Spitzer* Space Telescope, launched on 2003 August 25, has a 0.85-m primary mirror, originally cooled to 5.5 K. It has three instruments: IRAC (Infrared Array Camera), which operates simultaneously at four wavelengths (3.6, 4.5, 5.8, and  $8 \mu\text{m}$ ); IRS (Infrared Spectrograph) with four sub-modules operating at wavelengths 5.3–14 and 14–40  $\mu\text{m}$  (low resolution) and 10–19.5 and 19–37  $\mu\text{m}$  (high resolution); and MIPS (Multiband Imaging Photometer for *Spitzer*), three detector arrays for the far infrared at 24, 70, and 160  $\mu\text{m}$ .

Its first exoplanet observations included HD 209458 (Deming et al., 2005b), TrES-1 (Charbonneau et al., 2005), and the full-phase measurements of HD 189733 b (Knutson et al., 2007a). In 2009, Spitzer exhausted its liquid helium cryogen, precluding observations in the long-wavelength channels. At an equilibrium temperature of 30 K, IRAC continues observations at 3.6 and 4.5  $\mu\text{m}$  in the ‘warm Spitzer’ mode, in particular in the context of transit and eclipse spectroscopy, described further in Sections 6.24 and 11.6.

### 6.10.6 Others

**BRITE** The Bright Target Explorer (BRITE) Constellation of Austria, Canada and Poland consists of six nanosatellites with telescopes of 0.03-m aperture, launched on 2013 February 25, and surveying some 300 hundred of the brightest ( $V < 3.5$ ) stars (Schwarzenberg-Czerny et al., 2010; Weiss et al., 2014; Brosch et al., 2014; Zejda et al., 2016; Richardson et al., 2017). Each instrument has a wide field ( $\sim 24^\circ$ ), with up to 15 bright stars being monitored simultaneously. It was anticipated that BRITE might find transiting Neptune-sized planets around some of those monitored.

**SOFIA** The Boeing 747-based Stratospheric Observatory for Infrared Astronomy (SOFIA), equipped with a 2.5-m telescope and operating at  $\sim 12$  km altitude, was used for transit observations of HD 189733 (Angerhausen et al., 2010, 2015b). It was used with FLIPO (FLITECAM, combined with the High-speed Imaging Photometer for Occultations) for transit photometry of GJ 1214 (Angerhausen et al., 2017).

**STEREO-STRESS** The twin STEREO (Solar TERrestrial RElations Observatory) spacecraft were launched into solar orbits in 2006 to observe the Sun (Kaiser et al., 2008). The two wide-field heliospheric imagers, HI-1 and HI-2, have some  $10^6$  stars in their combined field. The STEREO TRansiting Exoplanet and Stellar Survey (STRESS) aimed to assess the use of the wide-field imagers for variable star and asteroseismology studies, with specific application to exoplanets (Wraight et al., 2011; Sangaralingam & Stevens, 2011; Whittaker et al., 2013). Transits should be detectable at depths of  $< 1\%$  for  $R \lesssim 10$ , and to  $\sim 0.2\%$  for  $R \lesssim 8$ , bringing detection of hot-Jupiters and possibly hot-Neptunes within reach (Whittaker et al., 2013).

## 6.11 Accuracy: photometric and timing

In the optical, wide-field surveys from the ground, such as HATNet and SuperWASP, are typically limited in precision by residual atmospheric effects to 2000–4000 ppm. Higher precision,  $< 1000$  ppm, has been demonstrated in some cases. For example, point-spread function shaping with the Orthogonal Parallel Transfer Imaging Camera at the UH 2.2-m telescope has achieved a precision of 470 ppm per 1.3-min sample (Johnson et al., 2009c). Transit measurements employing defocused observations have been reported at the level of 200–250 ppm for WASP-50 (Tregloan-Reed & Southworth, 2013).

From space, CoRoT and Kepler have demonstrated photometric precision in the optical at the level of some 15 ppm, limited in many cases by stellar variability.

For the bright ( $V = 7.65$ ) star HD 209458, HST observations achieved a precision of  $1.1 \times 10^{-4}$  (Brown et al., 2001), with a precision of  $3.5 \times 10^{-3}$  reported from MOST (Croll et al., 2007a). Ellipsoidal variations from Kepler are of amplitude  $3.7 \times 10^{-5}$  (Welsh et al., 2010).

In the infrared, state of the art for near- and mid-infrared detectors is defined by Spitzer and HST. Early Spitzer-IRAC photometry and HST-NICMOS spectroscopy suggested instrumental precision of around 100 ppm (e.g. Deming et al., 2006; Swain et al., 2009c), limited by detector non-linearity, point-spread function sampling, and long-term drifts in telescope pointing (Clanton et al., 2012). Improvements in Spitzer’s pointing stability improved the IRAC precision to better than 50 ppm (Demory et al., 2012).

In the ultraviolet, the observational characterisation of flares and stochastic fluctuations in the 120–150 nm spectra for 38 FM stars observed with HST-COS, and their predicted effects on transit signals, was reported by Loyd & France (2014).

**Future** A new generation of Teledyne H2RG (HgCdTe-based) detectors will be flown on three of the four JWST instruments (Rauscher et al., 2014), and possibly on ARIEL (Eccleston et al., 2015). Issues relevant for spectroscopic follow-up include sub-pixel non-uniformity (Barron et al., 2007), image persistence (Smith et al., 2008), and non-linearity or reciprocity failure (Biesiadzinski et al., 2011). High-precision time-series measures suggest that photon noise-limited precision of 10–20 ppm might ultimately be achievable (Clanton et al., 2012).

### 6.11.1 Stellar activity

The fundamental limits on high-accuracy time-series photometry, obtained above the Earth’s atmosphere, are imposed by the presence of stellar surface structure (star spots, plages, convective granulation, and non-radial oscillations), which are strong functions of spectral type. It is the same surface structure which sets limits on achievable radial velocity and astrometric accuracies. The relationships between them, parameterised by Eriksson & Lindegren (2007), are detailed in Section 3.3.4. The specific contribution of super-flares is considered in Section 8.10.6.

Aigrain et al. (2004) used solar irradiance power spectra from SOHO, and relationships between chromospheric activity, rotation period, and colour index, to predict the variability power on various time scales, and the impact of microvariability on the detection capability of transit searches as a function of stellar spectral type and age. For Kepler, at  $V = 12$  and with 10 min sampling, the smallest detectable planetary radii for 4.5 Gyr old G2, K0 and K5 stars, given a total of three or four transits in the light curves, were found to be 1.5, 1.0 and  $0.8R_\oplus$  respectively. Despite their higher variability, K-stars are promising transit candidates due to their small radius (see also Jenkins, 2002; Bonomo & Lanza, 2008).

Hydrodynamical models can be used to predict both photometric and astrometric jitter caused by photospheric granulation (e.g. Svensson & Ludwig, 2005; Ludwig, 2006; Cegla et al., 2013; Chiavassa et al., 2017).

Extensive time series measurements acquired with CoRoT and Kepler on thousands of stars over months to years, at levels previously possible only for the Sun, provide much information on stellar variability. Much of the short-time scale variability takes the form of stochastic noise, partly attributable to effects such as stellar granulation, which may limit progress in planet detection and characterisation (Gilliland et al., 2011a; Lanza, 2011; Balcerini et al., 2012; Miller et al., 2012; Basri et al., 2013; Cranmer et al., 2014; Kallinger et al., 2014; Bravo et al., 2014; Chiavassa et al., 2014; Gilliland et al., 2015b; Chiavassa et al., 2017; North et al., 2017b).

Many stars show periodic modulation attributed to, and well-modeled by, star spots and faculae, and these have led to detailed insights into rotation, and even differential rotation, in a large number of cases (§8.3), and to improved models of their effects on transmission and emission spectra (Zellem et al., 2017). The effects of absorption by the interstellar medium on activity measurements are detailed by Fossati et al. (2017b).

Some manifestations of stellar brightness variations observed by Kepler, termed *flicker*, are correlated with surface gravity and stellar density, irrespective of the presence of exoplanets (§6.29.2).

Modeling tools include *StarSim*, which generates photometric and spectroscopic time series based on a spotted rotating photosphere built from the spectral contribution of a fine grid of surface elements (Herrero et al., 2016). It includes various effects influencing the fluxes and wavelengths of spectral features produced by active regions and planets, and reproduces the photometry and radial velocity of HD 189733 to high precision.

### 6.11.2 Photometry from the ground

Nearby exoplanet host stars are typically comparatively bright, and telescope apertures can be very large. For bright star surveys, the contribution of photon noise to photometric transit measurements is accordingly generally negligible. Limitations on the smallest transit depths, and hence the smallest planet masses arise, instead, from atmospheric transparency variations, atmospheric scintillation noise, telescope tracking errors (partially addressed by high-precision autoguiding), and detector saturation and granularity.

Very stable sites in terms of atmospheric transparency fluctuations are required before scintillation dominates. If H<sub>2</sub>O drives the transparency fluctuations, telluric-line absorption variations may dominate longward of ~600 nm. The effects have been quantified by the statistical treatment of error propagation in the presence of red noise (e.g. Pont et al., 2006).

**Atmospheric influences on stellar images:** As described in Section 7.3, a wavefront incident on a telescope pupil experiences both phase and intensity fluctuations, both caused by refractive index variations within the turbulent atmosphere. Phase fluctuations are responsible for atmospheric ‘seeing’ and image motion, and can be (partially) corrected using adaptive optics.

*Scintillation* is a second-order effect (affecting the wavefront curvature). It results in the spatially and temporally varying intensity of starlight reaching the ground. Arising from the refocusing through turbulence (Dravins et al., 1997a), it is perceptible only at large distances from the disturbance, and is consequently dominated by high-altitude turbulence. Since the flux intercepted by the telescope undergoes rapid changes (due to photons falling outside of the telescope pupil when they should have been collected, and *vice versa*), the apparent brightness of the star flickers. The naked eye perceives the effect as ‘twinkling’. Adaptive optics may provide a diffraction-limited image, but its intensity still changes due to scintillation. Effects decrease to longer wavelength (Dravins et al., 1997b), and improve with the telescope diameter as  $D^{-2/3}$  (Reiger, 1963; Young, 1967; Kornilov, 2012).

Image intensity is also affected by atmospheric transparency variations, which can be largely corrected, in long-exposure imaging, through differential photometry with respect to comparison stars nearby on the sky. However, differential photometry corrects neither for phase fluctuations (unless the comparison star is within the isoplanatic patch), nor for scintillation effects. On the contrary, because of the high-altitude origin of scintillation, and the resulting small angular coherence scale of ~1 arcsec in the optical, calibration with respect to a comparison star tends to increase scintillation noise (Osborn et al., 2011).

In part because it is the phase component which dominates astronomical image resolution, and in part because of the restricted domains of astrophysical investigation which demand high-accuracy high-time resolution photometry (notably asteroseismology), efforts to correct for phase variations have been intensive and highly successful, while scintillation noise has received less attention.

Fundamental noise limits using fast photometry from the ground evidently have several contributions, but appear to be poorly quantified and not particularly well understood. An evaluation by Mary (2006) suggests that once transparency variations are suppressed, the overall noise is of a mixed Poisson nature, arising from photon noise mixed by scintillation. The photometric precision can be quantified by considering the various contributions to the signal-to-noise ratio (e.g. Collins et al., 2017b; Stefansson et al., 2017, eqn 1).

Broadly, ground-based transit photometry is limited to accuracies of a few mmag over relevant integration times. Ground-based telescopes are, consequently, presently able to discover exoplanet transits with depths up to about  $(\Delta F/F) \approx 1\%$  only, and are generally unable to observe secondary transits. It is the contributions from effects other than photon noise that lead to the majority of transit surveys being conducted from relatively small-aperture telescopes.



### 6.11.3 Defocused transits

Significant telescope defocusing, combined with long integration times (of several minutes), results in flat-fielding errors that can be averaged down by orders of magnitude compared to focused observations, decreasing sensitivity to individual pixels effects, and also meaning that normal changes in atmospheric seeing are irrelevant. The longer integration times and large point spread functions mean that the sky background level is much higher than for standard approaches, but signal-to-noise ratio calculations have shown that this is unimportant in many cases. For bright stars, more light to be collected per integration

**Observations** Observations using the ESO/Danish 1.54-m telescope with a point spread function of radius 17 arcsec (44 pixels) have shown improved rms scatter, of  $\sim 0.4$  mmag (400 ppm), for (according to publication date) WASP-5 (Southworth et al., 2009c), WASP-4 (Southworth et al., 2009a), WASP-2 (Southworth et al., 2010), WASP-17 (Southworth et al., 2012b), WASP-15 and WASP-16 (Southworth et al., 2013), WASP-24, WASP-25 and WASP-26 (Southworth et al., 2014), WASP-103 (Southworth et al., 2015a), and WASP-22, WASP-41, WASP-42 and WASP-55 (Southworth et al., 2016).

Defocused observations with the ESO NTT, with 170–200 s cadence, have an rms scatter of 200–250 ppm for WASP-50 (Tregloan-Reed & Southworth, 2013), some of the best to date. Other similar observations have been reported (e.g. Harpsøe et al., 2013; Baştürk et al., 2014; Tregloan-Reed et al., 2018).

**Transmission spectroscopy** Related experiments in *defocused transmission spectroscopy*, which aim to reduce systematic errors due to flat-fielding, point spread function variations, and slit-jaw imperfections, have been reported for WASP-12 using WHT-ISIS-QuCAM (Burton et al., 2015a).

### 6.11.4 Beam-shaping diffusers

A ‘diffuser’ is an optical component that uses microscopic surface or bulk structures to shape and homogenise light distribution. Types include ground-glass (sand-blasting to create small randomised surface features), holographic (recording of a speckle pattern in the diffuser substrate), and diffractive (based on fabricating a phase mask for a single central wavelength).

Stefansson et al. (2017) describe a new class of ‘engineered diffusers’, composed of individually manipulated unit cells or microlenslets and fabricated using a laser-writing process, which map the stellar image into a stable top-hat pattern (Figure 6.17). This aims to minimise atmospheric effects without defocusing the telescope. By spreading the light over many pixels, this allows the observation of bright stars without saturation, in the process minimising flat-fielding errors, atmospheric seeing effects, imperfect guiding, and telescope-induced variable aberrations. They do not specifically minimise scintillation noise (box, page 188).

With such observations using the ARC 3.5-m telescope, Stefansson et al. (2017) demonstrated 60 ppm

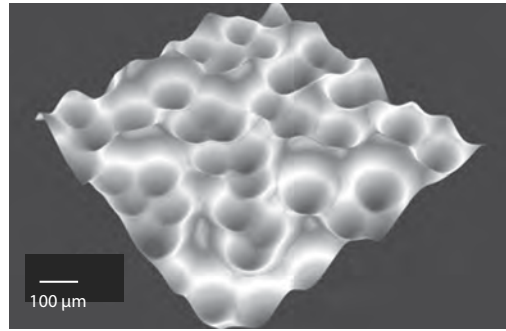


Figure 6.17: Scanning Electron Microscope image of the surface of an engineered beam-shaping diffuser, demonstrating a deterministic placement of surface features and microlenslets. Similar to Stefansson et al. (2017, Figure 4), this version kindly supplied by, and used with permission of, RPC Photonics.

precision ( $\sim 10^{-4}$ ) in 30-min bins on the bright ( $V = 6$ ) star 16 Cyg A (within a factor two or so of Kepler’s precision on the same star), and between 100–180 ppm for transits of WASP-85 ( $V = 11.2$ ) and TRÉS-3 ( $V = 12.4$ ). In the near-infrared, they demonstrated 140 ppm precision for a  $K_S = 10.8$  star on the Hale 200-inch telescope, comparable to that expected with TESS.

### 6.11.5 Conjugate-plane photometry

Osborn et al. (2011) proposed the concept of *conjugate-plane photometry* to improve scintillation noise (box, page 188). This involves conjugating the telescope pupil to the dominant high-atmospheric turbulent layer, then apodising it before calibration with a comparison star.

The method requires that the atmospheric inhomogeneities are concentrated within some relatively discrete layer(s), so that it is possible to define the limiting telescope entrance pupil corresponding to that altitude. Conceptually, an ‘oversized’ mirror collects the light that is sometimes refracted outside its nominal diameter.

Simulations of an atmosphere dominated by high-altitude turbulence suggest a reduction in intensity variance by a factor of 30, while models based on measurements at San Pedro Mártir suggest that a factor 10 in variance may be achievable (Figure 6.18). Other measurement and modeling efforts are ongoing (e.g. Föhning et al., 2015; Osborn, 2015; Osborn et al., 2015).

### 6.11.6 Timing accuracy

**Photon statistics** Even when ingress and egress are well sampled, the standard error on the mid-transit time cannot surpass that due to photon statistics (Holman & Murray, 2005, eqn 3)

$$\frac{\sigma_{t_c}}{t_T} \sim (S t_T)^{-1/2} \left( \frac{R_p}{R_\star} \right), \quad (6.4)$$

where  $t_T$  is the transit duration and  $S$  the stellar photon count rate. For the 0.95-m aperture Kepler,  $S \approx 7.8 \times$

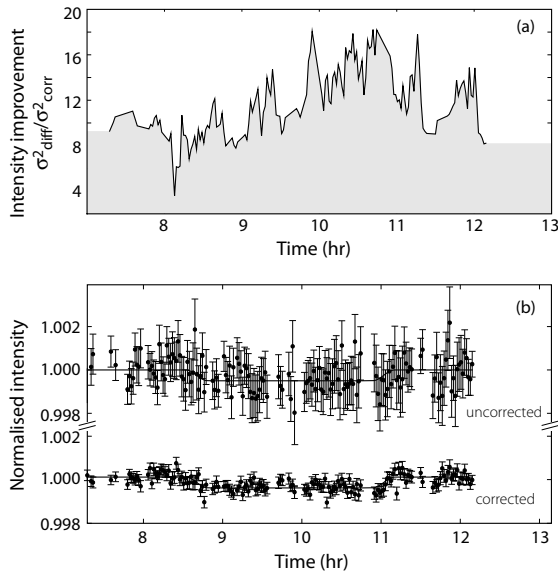


Figure 6.18: Conjugate-plane photometry: (a) expected (modeled) improvement factor in intensity variance as a function of time for data acquired from San Pedro Mártir on 2000 May 19; (b) simulated light curves of a secondary eclipse of an exoplanet with a transit depth of 0.05%, uncorrected (above) and corrected (below) for scintillation noise, assuming a 2-m telescope, and 30 s exposures in the V-band for a star of  $V=11$  mag. From Osborn et al. (2011, Figures 11–12), © Oxford University Press.

$10^8 10^{-0.4(V-12)} \text{h}^{-1}$ , such that a Jupiter-mass planet in a 1 au orbit around a  $1M_{\odot}$  star at  $V=12$  ( $t_{\text{T}} \approx 13 \text{h}$ ,  $R_{\text{p}}/R_{\odot} \approx 0.1$ ) gives  $\sigma_{t_c} \approx 20 \text{s}$ , while for a terrestrial-size planet  $\sigma_{t_c} \approx 500 \text{s}$ . Scaled to an 8-m telescope gives limits of 0.3 s and 10 s respectively.

**Transit times and ephemerides** The best achieved standard errors on transit mid-time accuracies reach 0.3 s in the case of the Kepler short-cadence data on TrES–2 b (Kipping & Bakos, 2011b) and, as given in the NASA Exoplanet Archive, in the range of 1–2 s in the case of Kepler–6, Kepler–12, WASP–19, and WASP–85.

Resulting accuracies on the ephemeris periods, especially for  $P \sim 1 \text{d}$ , can be as high as 0.01 s or better, reaching  $P = 0.788838989 \pm 0.00000004 \text{d}$ , i.e. a standard error of 0.03 s in the case of WASP–19 (Wong et al., 2016), and  $0.98678730 \pm 0.00000006 \text{d}$  in the case of Kepler–80 f (MacDonald et al., 2016).

## 6.12 Transit detection and light curve analysis

### 6.12.1 Detrending

The limiting factor for most transit surveys is not the theoretical photon noise but rather ‘red noise’ from non-astrophysical sources (Pont et al., 2006).

Specific effects in this category which hindered transit detection with CoRoT included discontinuities due

to high energetic proton flux near the South Atlantic Anomaly, residuals at the satellite orbital period, spacecraft jitter, CCD long-term ageing, and magnitude-dependent zero-points (Mazeh et al., 2009a).

Algorithms widely used for the calibration and correction of such red noise include, chronologically, TPS (Transit Planet Search), a wavelet-based algorithm including both detrending (PDC, Pre-search Data Conditioning) and detection, as used for Kepler (Jenkins et al., 2002, 2010c); SysRem, based on a principal component-type approach developed to correct for atmospheric extinction (Tamuz et al., 2005); CDA (CoRoT detrending algorithm Mislis et al., 2010a); EPD (External Parameter Decorrelation) for the removal of correlations with common parameters, e.g., air mass or chip position (Bakos et al., 2010); SARS (Simultaneous Additive and Relative System, Ofir et al., 2010); TFA (Trend Filtering Algorithm), which removes trends shared with other stars (Bakos et al., 2010; Penev et al., 2013); ACICA, for detrending using independent component analysis (Waldmann, 2014); ARC2 (Astrophysically Robust Correction 2), a systematics-correction pipeline for Kepler long-cadence light curves (Aigrain et al., 2017); DOHA, developed for the Qatar survey (Mislis et al., 2017); and MDCA, a modification to CDA emphasising short-term variability (Bouffleur et al., 2018).

Other considerations can be found in the literature (e.g. Mazeh & Faigler, 2010; Varón et al., 2011; da Silva & Silva-Valio, 2011; Petigura & Marcy, 2012; Kinemuchi et al., 2012; Stumpe et al., 2012; Smith et al., 2012c; Roberts et al., 2013b; Baran, 2013; Ofir et al., 2014).

An example of significant trend effects, before and after removal, are shown for the case of the multiple system Kepler–11 in Figure 6.19.

### 6.12.2 Transit detection

Transit detection algorithms aim to detect the signal of a transiting planet in the photometric time series of a star. The general characteristics of planet transits are short, small, and (generally) periodic decreases of the (assumed) constant luminosity flux of the star caused by the transiting planet.

**Algorithms** There is a large literature dealing with transit candidate detection techniques and algorithms, including (chronologically) matched filtering for eclipsing binaries (Jenkins et al., 1996); Bayesian methods (Defaÿ et al., 2001; Aigrain & Favata, 2002); effects of solar-like variability (Jenkins, 2002); BLS (Box-fitting Least Squares, Kovács et al., 2002; Enoch et al., 2012); TPS (Transit Planet Search), a wavelet-based algorithm including both detrending and detection (Jenkins et al., 2002, 2010c); fast identification (Protopapas et al., 2005); fast hybrid algorithms (Collier Cameron et al., 2006); approaches emphasising efficiency (Schwarzenberg-Czerny & Beaulieu, 2006); matched filtering (Bordé et al., 2007); wavelet analysis (Régulo et al., 2007); the ‘Hunter’ algorithm (Collier Cameron et al., 2007b; Triaud et al., 2011); spot models and harmonic fitting

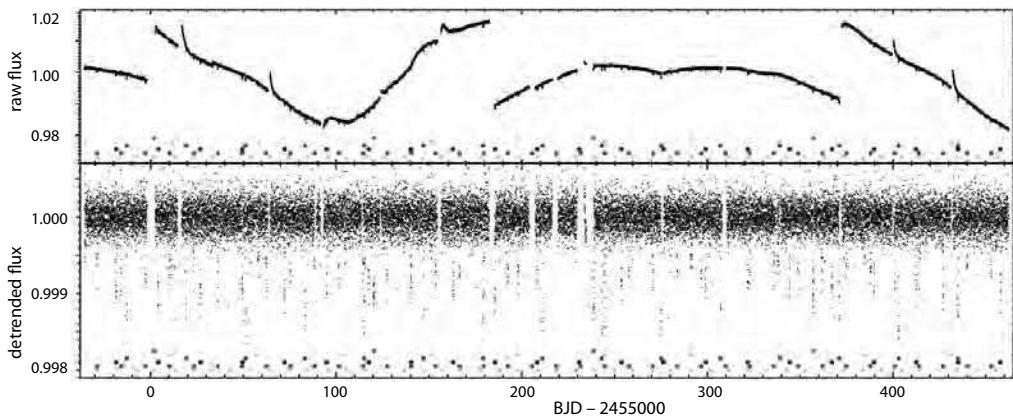


Figure 6.19: Detrended light curve of Kepler-11, in 30-min intervals. The six sets of periodic transits are indicated with dots of differing grey scale. From Lissauer et al. (2011a, Figure 1), by permission from Nature/Springer/Macmillan Ltd, ©2011.

(Bonomo & Lanza, 2008); period search without re-binning (Carpano & Fridlund, 2008); transiting circumbinary planets (Ofir, 2008); BAST, a BLS-like algorithm (Renner et al., 2008); inclusion of transit time variations (Carter et al., 2012); EXOTRANS, harmonic and trend filtering with BLS (Grziwa et al., 2012); DST (Détection Spécialisée de Transits), which includes consideration of the transit profile, as well as the presence of transit timing variations (Cabrera et al., 2012); TERRA, optimised to detect small planets around photometrically quiet stars (Pefigura et al., 2013b); Fourier transform for short-period candidate identification (Sanchis-Ojeda et al., 2014); QATS (Quasi-periodic Automated Transit Search), a BLS-like optimised for aperiodic signals (Carter & Agol, 2013); PASTIS (Planet Analysis and Small Transit Investigation Software, Moutou et al., 2014a; Santerne et al., 2015); and SIDRA (Signal Detection using Random-Forest Algorithm, Mislis et al., 2016).

**HAT-South** A detailed description of the data transfer and reduction from raw pixel images to trend-filtered light curves and transiting planet candidates is given by Bakos et al. (2013).

**CoRoT** Between 2004–2007 the CoRoT community evaluated the performance of various algorithms, finding comparable results, but with different non-detection and false-alarm rates (Moutou et al., 2005b, 2007a). The approach followed subsequently by the CoRoT community has been to use different detrending and detection techniques, aiming to extend the detection limits while limiting false alarm rates.

Widely used transit detection algorithms include BLS and DST, with a performance comparison given by Cabrera et al. (2012). DST has been used extensively since 2006 in the CoRoT survey analyses, e.g. for the fields IRa01 (Carpano et al., 2009), LRc01 (Cabrera et al., 2009), SRc01 (Erikson et al., 2012), LRA01 (Carone et al., 2012), and LRA03 and SRA03 (Cavarroc et al., 2012). A uniform analysis of the chromatic light curves, accounting for different limb-darkening parameters, was performed by Borsa & Poretti (2013). Further treatment is described by Weingrill (2015).

**Kepler** Kepler planet candidates are identified, and confirmed, following similar principles as for other transit programmes, although with particular challenges because of the large number of target stars, and with the typically fainter magnitudes making follow-up from ground (whether for confirmation or other scientific follow-up) more problematic.

The Kepler pipeline initially searches for transit signals using a single wavelet-based detrending and detection algorithm, TPS, the Transit Planet Search (Jenkins et al., 2002, 2010b,c; Tenenbaum et al., 2012; Christiansen et al., 2015). TPS requires three transits with a significance of  $7.1\sigma$  in order for the signal to be placed on a *threshold crossing event* list, and has searched for periods up to 525 d (Tenenbaum et al., 2012).

The waveforms used by TPS depend on just three parameters: epoch, period, and transit duration ( $t_0$ ,  $P$ ,  $d$  respectively), ignoring the exact shape of the depression (which depends on both stellar and planetary parameters), and aims only to identify interesting targets that should be followed up with the subsequent pipeline module, Data Validation (DV, Seader et al., 2013). The Data Validation stage performs a more rigorous fit to an astrophysical transit model to determine the validity of the threshold crossing event. Only threshold crossing events which pass additional tests, including a human review stage, become Kepler Objects of Interest (KOIs).

### 6.12.3 Kepler special cases

**Non-pipeline discoveries** The SARS pipeline, originally designed for CoRoT (Ofir et al., 2010), was used to re-examine Kepler Objects of Interest already known to include at least one promising candidate (Ofir & Dreizler, 2013; Ofir et al., 2014). Amongst 84 new transit signals in 64 systems, were Kepler-154 as a new 6-candidate system (of which kind only Kepler-11 was known before), and Kepler-974 c (KOI-1843.03) one of the shortest period (4.25 h) and smallest ( $0.63R_{\oplus}$ ) of all planet *candidates*. These types of studies have led to improvements, and subsequent detections, in the official Kepler pipeline, and the assignment of KOI and/or Kepler numbers as appropriate.

**Amateur networks** Several dozen candidates not found by the standard Kepler pipeline were identified by eye by public volunteers through the *Planet Hunters* ('citizen science') project (Fischer et al., 2012b; Conti, 2016; Edberg, 2016).

The Kepler light curves are broken into 30 d increments, and a visual analysis made to search for (perhaps more complex) transit signals missed by the TPS algorithm (Section 6.12). Between 2010–12, more than 250 000 public volunteers searched through more than 19 million Kepler light curves, contributing a cumulative total of 180 years of effort (Fischer et al., 2012b).

Statistical completeness has been assessed by injecting fake events into real Kepler light curves (Schwamb et al., 2012), demonstrating that the programme can detect transits of Neptune-sized planets or larger (with  $\geq 85\%$  completeness for short periods,  $P < 15$  d), although smaller planets may also be recovered.

The programme has discovered more than 40 planet candidates not already listed as KOIs (Fischer et al., 2012b; Lintott et al., 2013; Schwamb et al., 2012; Wang et al., 2013a; Schwamb et al., 2013). Of these, 33 have at least 3 transits (nine were detected with only two), 20 are potentially located in their habitable zones, and most have  $P_{\text{orb}} > 100$  d, with prospective periods  $> 400$  d. Confirmed (NASA-designated) discoveries include:

*Kepler-64 b* (PH-1 b): a circumbinary planet in a  $\sim 137$  d orbit around an eclipsing binary, and the first known planet in a quadruple star system (Schwamb et al., 2013);

*Kepler-86 b* (PH-2 b): a gas giant planet in its host star's habitable zone (Wang et al., 2013a);

*KIC-8462852* (Boyajian's star): this shows an unusual, complex, and aperiodic light curve (see §6.14.22).

**Short-period planets** Various independent searches of the publicly-available Kepler data set have focused explicitly on the search for very short orbital periods,  $\leq 1$  d, for which the Kepler pipeline had not yet been optimised (Ofir & Dreizler, 2013; Jackson et al., 2013; Huang et al., 2013; Sanchis-Ojeda et al., 2014).

Jackson et al. (2013) reported four candidates with  $P < 12$  h, using photometric models that include transits, ellipsoidal variations, and secondary eclipses to constrain the radii, masses, and temperatures. Even with masses of only a few  $M_{\oplus}$ , the short orbital periods mean that they may induce stellar radial velocity signals at a few  $\text{m s}^{-1}$ . These very short-period planets may be the remnants of disrupted hot Jupiters.

Huang et al. (2013) performed a search for planet candidates in the publicly available Kepler long-cadence data from quarters Q1–Q6, comprising data de-trending, trend filtering, searching for transit signals with BLS in three frequency domains, visual inspection of potential candidates, and an in-depth analysis of shortlisted candidates. They presented 150 new periodic candidates and seven single transit events, 72 of which are in multiple systems. Periods vary from 0.17–440 d. Of the entire set of candidates, 124 have  $R_{\text{p}} < 3R_{\oplus}$ . They recovered 82.5% of the Batalha et al. (2013) KOI catalogue.

Departing from a BLS-based analysis, Sanchis-Ojeda et al. (2014) used a Fourier transform approach, aimed at discovering very short period planets with  $P \leq 1$  d. Applied to the photometric time series for all 200 000 target stars, they identified transit signals based on the presence of regularly spaced sharp peaks in the Fourier spectrum, resulting in 106 candidate short-

period planets, of which 18 had not been previously reported.

Working with the augmented number of seven (candidate) planets with  $P < 6$  h, and assuming that the relatively high fraction of multi-transit candidates represent co-planar systems, Sanchis-Ojeda et al. (2014) inferred that such *ultra-short period planets* are typically accompanied by other planets with periods 1–50 d (in contrast with hot Jupiters which rarely have companions in that same period range). Another clear pattern is that almost all ultra-short period planets have  $R_{\text{p}} < 2R_{\oplus}$ , presumably as a result of atmospheric loss through photoevaporation from stellar irradiation. Based on their survey statistics, ultra-short period planets exist around  $0.51 \pm 0.07\%$  of G dwarfs, and  $0.83 \pm 0.18\%$  of K dwarfs (Figure 6.20).

For the 50 shortest period candidates, with eccentricities from transit and secondary eclipse data, Shabram et al. (2016) found that a 2-component Gaussian for  $e \cos \omega$  and  $e \sin \omega$  gave a better fit than Rayleigh or Beta distributions (§2.10.4). They inferred that 90% are from a population with a small eccentricity dispersion ( $\sim 0.01$ ), and the others from a population with a larger dispersion ( $\sim 0.22$ ), consistent with the majority resulting from gas disk migration, and the remainder from Lidov–Kozai oscillations or planet–planet scattering (§10.10.6).

**Long-period planets** Long-period transiting planets are rare, due to a combination of their infrequent transits, and their smaller geometric transit probability (see Kepler statistics, §6.26.3). Some of the longest transiting periods known are either from ground-based follow-up of radial velocity detections (§6.3.1), or as single transit events in the light curves of systems in which inner transiting planets were already known (§6.26.3). Other long-period Kepler planets are non-transiting outer companions to transiting planets which were subsequently discovered through radial velocity measurements.

In other specific configurations, Murphy et al. (2016) discovered a long-period planet (Kepler-1648,  $P = 840 \pm 20$  d,  $e = 0.15$ ) from the host A star's pulsational phase shifts induced by its barycentric orbital motion.

**Events with only one or two transits** As noted in Section 6.12.2, the Kepler pipeline candidate detection requires three transits with a significance of  $7.1\sigma$  in order for the signal to be placed on a *threshold crossing event* list, and searches for periods up to 525 d. But various specific searches have been made based on the presence of just one or two transits.

K2-2 b was initially noted in a single transit during 6.5 d of engineering data, and subsequent follow-up with HARPS spectroscopy and MOST photometry confirmed a  $2.5R_{\oplus}$  planet on a  $P = 9.1$  d orbit (Vanderburg et al., 2015b). Although not of long-period, it demonstrates discovery possibilities based on a single transit.

The orbital period of a transiting planet with only a single transit can still be constrained given a measurement of  $\rho_{\star}$  (cf. §6.13.5, §6.13.7) and an assumption about the orbital eccentricity (e.g. Wang et al., 2015a; Osborn et al., 2016). Unlike general transit models which rely on  $P$  (or  $a$ ) to estimate the planet's velocity, Osborn et al. (2016) used a single transit estimate (their eqn 1)

$$v' \equiv \frac{v_{\text{orb}}}{R_{\star}} = \frac{2\sqrt{(1 + R_{\text{p}}/R_{\star})^2 - b^2}}{T_{\text{D}}}, \quad (6.5)$$

with  $b$ ,  $R_{\text{p}}/R_{\star}$  and  $T_{\text{D}}$  derived from the transit shape. A circular period  $P_{\text{circ}}$ , for  $e = 0$ , can then be estimated from Kepler's law

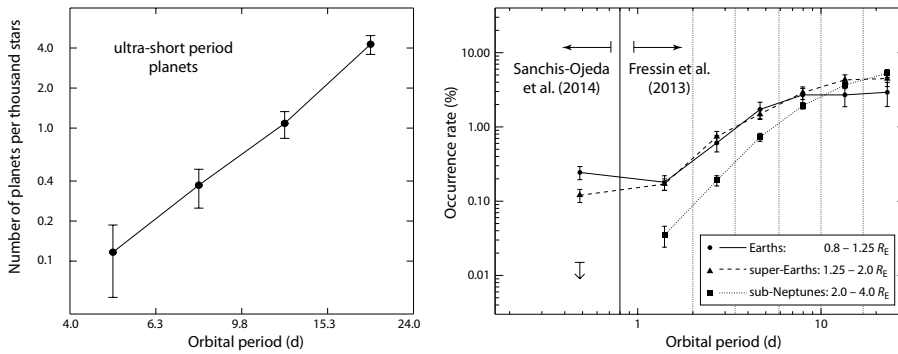


Figure 6.20: Occurrence rate for ultra-short-period planets, taking into account the implied number of non-transiting planets, as well as the number of stars that were effectively searched for such a planet. Left: as a function of orbital period. Integrated over all radii and  $P < 1$  d, the total occurrence rate is  $5.5 \pm 0.5$  planets per thousand stars, and decreases with decreasing orbital period. Right: occurrence rates for Earths, super-Earths, and sub-Neptunes planets as a function of orbital period. The data points for  $P > 0.8$  d are from Fressin et al. (2013), and the shortest-period data point is from Sanchis-Ojeda et al. (2014). From Sanchis-Ojeda et al. (2014, Figures 9 and 10), by permission of IOP Publishing/AAS.

as (Osborn et al., 2016, eqn 2)

$$P_{\text{circ}} = \frac{8\pi^2 G}{3} \frac{\rho_{\star}}{v^3} = 2\pi \frac{g}{R_{\star} v^3}. \quad (6.6)$$

Qualitatively, this follows from the fact that the transit of a bound body cannot have an arbitrary period for a given transit duration. This is the same argument used to justify the ‘photoeccentric effect’ (§6.13.11) and the method of ‘asterodensity profiling’ (§6.13.11). It also suggests that the periods of single transits in systems with multiple inner planets will be especially well constrained (Kipping et al., 2012b).

Osborn et al. (2016) applied the technique to seven candidates identified from K2 campaigns 1–3. One candidate has  $P = 540^{+410}_{-230}$  d and  $R_p = 0.51 \pm 0.05 R_J$ , with six further candidates meriting follow-up.

Uehara et al. (2016) visually inspected light curves of 7557 KOIs to search for single transits, and identified 28 events in 24 KOIs, with 14 new. They estimated  $P$  and  $R_p$  by fitting the light curves simultaneously with the transits of other planets in the system, or with prior information on  $\rho_{\star}$ , finding 7 consistent with Neptune- to Jupiter-sized objects with  $P \lesssim 20$  yr.

Foreman-Mackey et al. (2016) made an automated search for 1- or 2-transit systems applied to the brightest 40 000 solar-type stars, finding 16 long-period candidates (including, for example, a long-period planet e in the already known Kepler-167 system). They estimated an occurrence rate for solar-type stars, for  $R_p < R_J$  and  $P = 2 - 25$  yr, to be  $2.0 \pm 0.7$  planets per star.

These and other long-period candidates, from TESS, PLATO, or NGTS, should reside in orbital domains suitable for astrometric confirmation by Gaia.

**Small planets** Optimised to detect small planets around photometrically quiet stars, TERRA was used to search the quietest 12 000 Kepler stars (Petigura et al., 2013b). They reported 129 candidates with  $R_p < 6R_{\oplus}$  in 3 years of data (quarters 1–12), a third of them new. They found a power-law rise extending from  $5.7R_{\oplus}$  down to  $2R_{\oplus}$ , as found by Howard (2013), but thereafter flattening off and constant between  $2R_{\oplus}$  towards  $1R_{\oplus}$ . They estimated that some 15% of solar type stars has a  $1 - 2R_{\oplus}$

planet with  $P = 5 - 15$  d. Other searches have been reported by Howell et al. (2016a).

**Keplerian orbits** For transiting planets explicitly described by Keplerian orbits, algorithms to optimise computationally-intensive searches in very long data sets have been developed (Ofir, 2014a). Cubic frequency sampling, and duty-cycle dependent binning, lead to computational gains over the (standard) BLS by a factor 300 for a 3-yr data set, at the same time enhancing detectability of both short- and long-period planets.

**Circumbinary planets** In contrast with planets orbiting single stars, planets orbiting stellar binaries result in varying transit times, durations, and depths, all depending on the phase of the binary (Schneider & Chevreton, 1990; Schwarz et al., 2011; Armstrong et al., 2013). As a result, the search for transiting circumbinary planets becomes more complex, and the more standard transit search algorithms such as BLS fail (Orosz et al., 2012a; Kostov et al., 2013).

Specific considerations have been assigned to planets orbiting eclipsing binaries, in which the nearly edge-on inclination significantly increases the probability of transits (Borucki & Summers, 1984), and other circumbinary or circumprimary/secondary configurations, the latter exemplified by the discovery of  $\alpha$  Cen B b (Dumusque et al., 2012).

Several approaches have been proposed. One is based on simulating a library of possible orbits of circumbinary planets, and fitting them to the light curve (Doyle et al., 2000; Ofir, 2008).

Carter & Agol (2013) developed the QATS algorithm (Quasi-periodic Automated Transit Search), which is similar to BLS but optimised for aperiodic signals, and applied it to searches around eclipsing binary stars listed in the Kepler catalogue of Slawson et al. (2011).

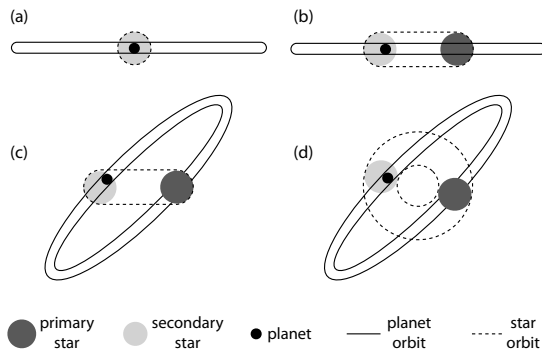


Figure 6.21: The four possible transit configurations for single and binary stars. In each case, the planet moves within the solid lines, around single and binary stars that move within the dashed lines. (a) transit of a single star; (b) transit of an eclipsing binary by a co-planar planet, the planet transiting both stars every orbit; (c) transit of an eclipsing binary by a misaligned planet; (d) transit of a non-eclipsing binary by a misaligned planet. In cases (c) and (d) the planet and binary orbits overlap, but transits will not occur at every period due to the relative motion of the bodies. From Martin & Triaud (2014, Figure 1), reproduced with permission © ESO.

As a consequence, the number of Kepler circum-binary planets rose from zero to seven, including a multi-planet system with one of the planets in the habitable zone (Kepler-47), as improvements were made in the recognition of their transit timing and duration variation signatures (Welsh et al., 2014). A list of eclipsing binaries that may have planetary systems was given by Tutukov & Bogomazov (2012).

Martin & Triaud (2014) considered the prospects for the discovery of planets around the much larger fraction of non-eclipsing binaries, concluding that such planets are probably present in the Kepler data. Figure 6.21 shows the four possible transit arrangements for single and binary stars.

**Circumprimary planets** While some dozen transiting planets have been found in wide orbits around an inner, close stellar binary, none has yet been detected orbiting only one component of an eclipsing binary, despite some 3000 such systems having been discovered by Kepler (§6.6.6). Oshagh et al. (2017) developed a specific detection method for these S-type planets, exploiting a correlation between the stellar radial velocities, eclipse timing variations, and eclipse duration variations.

**Visual inspection and others** Other specific transit cases have been searched for by specific binning procedures, as in the case of Trojan searches (§6.21) and exomoon searches (§6.22), or by visual inspection, including the exocomet candidates (§6.23).

**Automation and machine learning** A number of automated detection and classification methods are now

being developed, providing a route to sample uniformity important for population studies. More generally, *machine learning* targets the development of algorithms that, unlike static program instructions, can learn from and make data predictions through models building on sample inputs. It is employed where designing explicit algorithms with good performance is difficult or unfeasible (e.g. email filtering, and speech recognition).

Amongst the subsets (supervised, unsupervised, semi-supervised, and reinforcement), the most relevant in exoplanet studies to date is *supervised learning*, in which explicit training examples are provided, consisting of an input object and a desired output value. Within the category of supervised learning, widely used learning algorithms include support vector machines, linear regression, decision trees,  $k$ -nearest neighbours, and neural networks. *Deep learning* comprises a multilayer stack of simple modules, all of which are subject to learning, and many of which compute non-linear input-output mappings. Each module transforms its input to increase both selectivity and representational invariance. Deep learning is making major advances in areas such as image recognition, speech recognition, and language translation (Lecun et al., 2015).

**Transit applications** *Autovetter* exploits machine learning to vet Kepler threshold crossing events (McCauliff et al., 2015), using a ‘random forest model’ for classification based on features from Kepler pipeline statistics. A similar approach, *SIDRA*, was developed by Mislis et al. (2016). *Robovetter* is based on a decision tree, and is designed to mimic the manual process of rejecting false-positive threshold crossing events. It has been used to produce the more recent fully automated catalogues (Coughlin et al., 2016; Thompson et al., 2018).

Unsupervised machine learning has been used to cluster Kepler light curves with similar shapes, and to define classification metrics using the distances between new light curves and threshold crossing events with known characteristics (Thompson et al., 2015; Armstrong et al., 2017). The LPP (Locality Preserving Projections) metric defined by Thompson et al. (2015) is used by *Robovetter* to filter out light curves with ‘non-transit-like’ shapes. Millholland & Laughlin (2017b) used supervised learning to identify candidate non-transiting planets. Dittmann et al. (2017b) used a neural network to identify candidates in MEarth data.

Dehghan et al. (2017) developed an unsupervised method for correlated noise removal for multi-wavelength transit observations, using ‘ $k$  means clustering’ and ‘Silhouette clustering’ (methods of vector quantisation, originally from signal processing, used for cluster analysis in data mining).

Shallue & Vanderburg (2018) applied a deep *convolutional neural network* for automatically vetting threshold crossing events, using light curves as inputs and trained on a set of human-classified events. They reported the discovery of the 8th planet in the Kepler-90 (KOI-351) system, and the 6th planet (part of a 5-planet resonant chain) in Kepler-80 (Figure 6.22).

Confirmation that such approaches successfully detect periodic transits consistent with the true period without any model fitting, indicates that machine learning should facilitate the discovery and characterisation of exoplanets in large data sets in the future (Pearson et al., 2018; Zucker & Giryes, 2018).

### 6.12.4 Light curve fitting

The principles of light curve fitting is similar across the various transit survey groups, although details vary. The relevant literature is indicated in the following.

**Transit Analysis Package, TAP** The Transit Analysis Package, TAP, is widely used, for example, by the Kepler and HAT teams (Fulton et al., 2011; Gazak et al., 2012; Hoyer et al., 2012; Maciejewski et al., 2013a). It fits 13 parameters (with error estimates) to the observed light curve, nine of which characterise the physical system: mid-transit time  $T_C$ , orbital period  $P$ , inclination  $i$ , eccentricity  $e$ , argument of pericentre  $\omega$ , normalised semi-major axis  $a/R_\star$ , normalised planet radius  $R_p/R_\star$ , and limb darkening coefficients for a quadratic limb darkening law ( $u_1$  and  $u_2$ ).

**Detailed treatment** In addition to the physical parameters, the fit includes a linear slope to account for a possible linear trend with time during the transit,  $S$ , a flux normalisation factor,  $N$ , and two noise components: a temporally uncorrelated Gaussian ‘white’ noise,  $\sigma_w$ , and a time-correlated ‘red’ noise,  $\sigma_r$  (Carter & Winn, 2009, equations 32–34), where a power spectrum density of  $1/f$  is assumed. Search optimisation frequently employs the method of Monte Carlo Markov Chains (MCMC, e.g., Ford, 2005, 2006b; Holman et al., 2006; Collier Cameron et al., 2007b; Burke et al., 2007). To account for possible temporally correlated noise (e.g. Pont et al., 2006) it uses the wavelet likelihood approach of Carter & Winn (2009).

To measure the quality of a given light curve, Fulton et al. (2011) introduced the photometric noise rate, defined as  $\text{PNR} = \text{rms}/\sqrt{T}$  where the rms of the residuals is derived from the light curve and a fitted model, and  $T$  is the median number of exposures per minute.

As used by the WASP collaboration, data reduction follows a similar procedure, typically using an MCMC search algorithm (Collier Cameron et al., 2007a; Bouchy et al., 2008; Gillon et al., 2008; Wilson et al., 2008a; Gillon et al., 2009a; Triaud et al., 2009, 2011; Anderson et al., 2011d; Gillon et al., 2012b; Lendl et al., 2012; Triaud et al., 2013a; Maciejewski et al., 2013a).

The code allows the combination of photometry and spectroscopy, with a common set of free parameters from which the physical parameters, specifically: period  $P$ , mid-transit time  $T_0$ , transit depth  $D$ , transit width  $W$ , impact parameter  $b$ , and semi-amplitude of the stellar Doppler reflex motion  $K$ . They used models from Mandel & Agol (2002) to fit the photometric transit and from Giménez (2006b) to adjust the Rossiter–McLaughlin effect as well as a classical Keplerian model for the orbital variation in the radial velocities. Limb darkening coefficients for the quadratic law were from Claret (2000, 2004) for the photometry.

Fits to the Rossiter–McLaughlin effect use  $\sqrt{V \sin i} \cos \beta$  and  $\sqrt{V \sin i} \sin \beta$  where  $V \sin i$  is the projected stellar rotation and  $\beta$  the projected spin–orbit angle. Eccentricity terms used are  $\sqrt{e} \cos \omega$  and  $\sqrt{e} \sin \omega$  (the more traditional  $e \cos \omega$  and  $e \sin \omega$  amounts to imposing a prior proportional to  $e^2$  (Ford, 2006b)), as well as radial drift and normalisation terms. Results show a (strong) degeneracy between  $\beta$  and  $V \sin i$  (Narita et al., 2010a; Triaud et al., 2010). A prior on the projected stellar rotation velocity can be based directly on an analysis of the spectral lines, or through activity–rotation relations based on Ca II emission (Noyes et al., 1984; Mamajek & Hillenbrand, 2008).

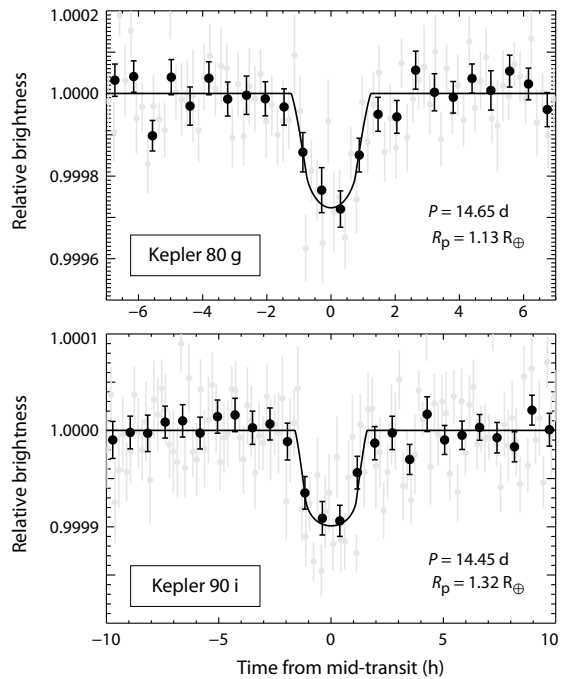


Figure 6.22: Light curves and best-fit models for Kepler–80g and Kepler–90i, discovered by means of a convolutional neural network. Grey points are  $\sim 10$  min averages. Solid circles are averages over  $\sim 0.25$  of the transit duration ( $\sim 30$  min for Kepler–80g, and  $\sim 45$  min for Kepler–90i). From Shallue & Vanderburg (2018, Figure 12), by permission of IOP Publishing/AAS.

**Other light curve fitting algorithms** Other algorithmic implementations are reported in the literature, some of which can include a joint fitting of transit and radial velocity data if available. More recent algorithms extend the analysis to secondary eclipses and phase curves, as discussed in later sections.

EXOFAST was developed to fit transits and radial velocity variations simultaneously or separately, and to characterise parameter uncertainties and covariances, with a differential evolution Markov chain Monte Carlo method (Eastman et al., 2013).

JKTEBOP was originally developed for detached eclipsing binaries, and adapted for transit light curves (Southworth, 2013). It determines the orbit inclination  $i$ , the transit mid-time  $T_0$ , and the sum and ratio of the fractional radii of the star and planet (and masses and radii if radial velocities are supplied). It represents the star and planet as biaxial spheroids for the reflection and ellipsoidal effects, and as spheres for the eclipse shapes, and includes the Claret 4-parameter limb darkening law.

CurveFit–WinKepler is a comparable light curve fitting modified from close binary analysis (Rhodes & Budding, 2014).

PyTransit is a package implementing optimised versions of the Mandel & Agol (2002) and Giménez (2006a) transit models (Parviainen, 2015a,b).

BATMAN, BAsic Transit Model cAlculationN in Python (Kreidberg, 2015a,b), models transits with a fast C-based analytical integrator, making it suitable for use with MCMC analysis.

SPIDERMAN extends the modeling to eclipses and phase curves in a self-consistent way for arbitrary brightness distributions (Louden & Kreidberg, 2017). The planet is divided into a small

number of regions, the area of each region not occulted by the star is calculated geometrically, and the average surface brightness of each region is determined by the chosen model and multiplied by the visible area to get the total flux.

The von Mises periodogram is a generalised linear least-squares (Lomb–Scargle) periodogram for non-sinusoidal signals with a non-linear dependence on unknown parameters (Baluev, 2013c). The signal is modeled by the periodic function  $\exp(v \cos \omega t)$ , in which the non-linear parameter,  $v$ , can model different periodic types, from a sinusoid, to one with periodic narrow peaks or drops typical of exoplanet transits.

NAMASTE, MCMC Analysis of Single Transiting Exoplanets, for long-period planets (§6.12.3), models a single transit occurrence with a planet velocity scaled to  $R_*$  (Osborn et al., 2016).

TEE, Timing Error Estimator, precision estimator for eclipse and transit minimum times (Deeg & Tingley, 2017).

Other fitting algorithms, frequently based on the models of Mandel & Agol (2002), some combining transit and radial velocity data, and some dedicated to the modeling of exomoons and rings, include `ellc` (Macted, 2016), `exorings` (Kenworthy & Mamajek, 2015b,a), `GP-EBOP`, a Gaussian-process version of EBOP (Gillen et al., 2017), `mttr` (Pál, 2012), `PHOEBE 2.0` (Prša et al., 2016), `pyaneti` (Barragán et al., 2016), `TAC-maker` (Kjurkchieva et al., 2013b,a), and `UTM` (Deeg, 2009, 2014).

Algorithms specifically taking into account transit times are noted in Section 6.20.4, while those specifically taking into account star spots are noted in Section 6.14.2.

### 6.12.5 Candidate confirmation

A regular transit-type signature cannot be taken as unambiguous evidence for a transiting planet. For example, while the fractional brightness changes in a binary-star eclipse are normally much larger, occasionally such an eclipse is grazing, or light from the star is diluted or ‘blended’ with light from a background or companion eclipsing binary nearby on the plane of the sky. Such false-positives plague both ground and space searches (e.g. Evans & Sackett, 2010; Barclay et al., 2013a).

In consequence, before upgrading a periodic transit-like signal from a candidate to a confirmed planet, other possibilities must first be excluded. False signals include stellar binaries with grazing eclipses; background eclipsing binaries; background star–planet systems; eclipsing binaries in a hierarchical stellar triple system; eclipsing binaries presenting only secondary eclipses; and a planet orbiting a physical stellar companion.

The most robust confirmation can be obtained from radial velocity measurements which, for an orbit edge-on to the line-of-sight, provides a rather unambiguous estimate of the companion mass.

Since the majority of the Kepler host stars are faint, making radial velocity measurements impractical if not impossible, other tests have been formulated. While many of the following considerations apply to transit searches more generally, most have been developed in the context of the Kepler candidate evaluation.

**Kepler specifics** In the case of Kepler with its large number of transit candidates simultaneously present in the field, instrumental effects can also generate false candidates (Caldwell et al., 2010; Coughlin et al., 2014). These can arise from reflections from the fused-quartz Schmidt corrector plate, reflections from the 42 individual field flattener lenses which map the spherical telescope image onto the CCDs, CCD cross-talk, and CCD ‘column anomalies’. Bayesian methods to identify these are described by (Mullally et al., 2016).

For these astrophysical and instrumental reasons, the successive transit detections (Tenenbaum et al., 2012, 2013, 2014; Seader et al., 2015; Twicken et al., 2016) and catalogues initially assembled by the Kepler project (Borucki et al., 2011b; Batalha et al., 2013; Burke et al., 2014; Rowe et al., 2015; Mullally et al., 2015; Coughlin et al., 2016) are considered to be only planet *candidates*, and various other tests or observations are required to *validate* each candidate on a case-by-case basis.

Results of the final (17 quarters) Kepler planet search (Twicken et al., 2016) includes 198 709 stellar targets (of which 112 046 were observed in all 17 quarters), 17 230 targets for which at least one transit signature is identified that meets the specified detection criteria: periodicity, minimum of three observed transit events, detection statistic in excess of the search threshold, and passing grade on three statistical transit consistency tests.

**Kepler false-positive rate** Various studies have suggested that false-positive rates as a whole are probably less than 10%, such that most KOI candidates are indeed true planets (Morton & Johnson, 2011b). The false-positive rate depends on  $R_p$ , with the lowest rate (6.7–8.8%) in the range of  $1.25 - 6.00R_\oplus$ , although appearing higher for the largest planet candidates (Morton & Johnson, 2011b; Santerne et al., 2012a; Fressin et al., 2013; Coughlin et al., 2014). For example, Fressin et al. (2013) found a global false-positive rate of 9.4%, peaking at 17.7% for giant planets ( $6 - 22R_\oplus$ ), reaching a low of 6.7% for small Neptunes ( $2 - 4R_\oplus$ ), and increasing again to 12.3% for Earth-size planets ( $0.8 - 1.25R_\oplus$ ).

Morton et al. (2016) derived astrophysical false-positive probability calculations for every Kepler Object of Interest (KOI): out of 7056 KOIs, they estimated that 1935 have probabilities  $< 1\%$  of being astrophysical false-positives, and thus may be considered validated planets. Of these, 1284 had not yet been validated or confirmed by other methods.

Eclipsing binaries presenting only secondary eclipses may mimic a planetary transit. Santerne et al. (2013) estimated that  $0.061 \pm 0.017\%$  of main-sequence binary stars are secondary-only eclipsing binaries that mimic a planetary transit candidate with  $R_p \geq R_\oplus$ .

The expected false-positive rate for candidate multi-planet systems is very low, estimated at approximately only two out of all Kepler targets (Lissauer et al., 2012b).



**Detailed consideration of false-positives:** Examination of the raw flux, pixel flux, and flux-weighted centroids of each Kepler KOI establishes the likelihood of it being an astrophysical false-positive or a planetary companion. Viable planet candidates are identified through various tests (e.g. Borucki et al., 2011a,b; Morton, 2012; Batalha et al., 2013; Bryson et al., 2013; Seader et al., 2013; Burke et al., 2014; McCauliff et al., 2015), including (1) verifying that alternating transit events have the same depth, which they may not if the signal is due to a background eclipsing binary; (2) checking for the presence of shallow secondary eclipses, which are common in eclipsing binaries but are not expected for the smallest planets; (3) checking for ellipsoidal variations, which could be another sign of a blend; (4) checking for changes in the centroid positions correlated with the brightness changes, which might indicate a blend, or a crowded aperture.

Catalogues of known transiting planets, eclipsing binaries, and variable stars have also been compiled as a list of potential contaminating sources, and used to assist identification of false-positives through *ephemeris matching*, viz. examining whether photometric variability in a transit candidate matches that from a known variable source elsewhere in the field (Coughlin et al., 2014).

Successful candidates are submitted to ground-based observers for further false-positive elimination or confirmation and characterisation (Gautier et al., 2007; Latham, 2008a; Yee & Gaudi, 2008). Many different techniques have been developed to verify or validate the candidates, including dynamical confirmation by detection of either transit timing variations in the Kepler light curve or radial velocity variations, or based on statistical arguments showing that the likelihood of the planet hypothesis is much greater than that of other possible causes of the observed light curve (Torres et al., 2011; Morton, 2012; Lissauer et al., 2014b).

**Pre-spectroscopic elimination of false-positives** The first steps of data validation (Jenkins et al., 2010c; Batalha et al., 2010b; Steffen et al., 2010; Morton & Johnson, 2011b) examine the time-series light curves for transit-like events, termed *threshold crossing events*, each having a total detection statistic above  $7.1\sigma$ . Light curves are modeled as star–planet systems, with those returning a companion radius  $< 2R_J$  assigned a Kepler Object of Interest (KOI) number (see box).

While many of the confirmed Kepler planets have been published individually, or in small groups, a number of papers have presented more large-scale confirmations. These include: 27 from transit time variations (Steffen et al., 2013); 12 multiple system candidates from transit time variations of near resonance pairs (Xie, 2013); several hundred from the statistics of multi-planet systems (Lissauer et al., 2012b, 2014b; Rowe et al., 2014); and several hundred from various photometric analyses.

**Confirmation techniques** Only candidates verified to be true planets at a high level of confidence (typically, well above 99%) are assigned designations of the form Kepler–NNN. The various techniques that have been developed to reject false-positives or confirm preliminary candidates are listed below. Some are particularly relevant only for Kepler, but most have wider applicability.

- *Confirmation from blend properties:* Use of the light curves themselves is widely used to help discriminate between true planet transits and a variety of possible blend scenarios, and is of particular value in validating the smallest planets which may fall below radial velocity detection limits (Torres et al., 2004b; Fressin et al., 2011; Steffen et al., 2010; Torres et al., 2011).

The idea underlying the BLENDER tool (Torres et al., 2004b, 2011) is to compare the transit photometry of a candidate against synthetic light curves produced by an eclipsing binary that is included within the photometric aperture. In principle there is an extensive range of possible binary configurations that could mimic all of the features of true planetary transits, including their depth, the total duration, and the length of the ingress and egress phases. Possible scenarios include background eclipsing binaries, and also hierarchical triples, i.e., an eclipsing binary physically associated with the candidate in a wide orbit around the barycentre.

Brightness variations of an eclipsing binary are generated with binary light-curve code such as EBOP (Popper & Etzel, 1981), and then diluted by the light of the candidate. Effects such as limb darkening, gravity brightening, mutual reflection, and binary component oblateness can be included. Example applications include CoRoT–7 b (Fressin et al., 2012a); Kepler–9 d (Torres et al., 2011); Kepler–10 b (Batalha et al., 2011); and Kepler–20 e and f (Fressin et al., 2012b). An alternative but similar implementation is PASTIS (Planet Analysis and Small Transit Investigation Software), described by Díaz et al. (2014a), and applied to various systems, including CoRoT–2 (Bruno et al., 2016), CoRoT–22 (Moutou et al., 2014a), Kepler–420 (Santerne et al., 2014), and K2–19 (Armstrong et al., 2015b).

A related technique employing high-resolution slit spectroscopy and libraries of combined model spectra, aiming to identify background stars or binary hosts, identified 63 KOIs with spectroscopic evidence for a secondary star within  $0.87 \times 3 \text{ arcsec}^2$  (Kolbl et al., 2015). Other transit validation and false probability estimation algorithms include CORBITS (Brakensiek & Ragozzine, 2016) and VESPA (Morton, 2012, 2015).

- *Confirmation from imaging:* High-resolution ground-based imaging has been widely used to identify neighbouring stars that might be eclipsing binaries with the potential to cause perturbing transit-like signals (see also §7.9.3).

The Robo–AO Kepler Planetary Candidate Survey is observing every candidate host star with adaptive optics imaging (Law et al., 2014c; Baranec et al., 2016). The survey is sensitive to separations 0.15–2.5 arcsec, with  $\Delta m \lesssim 6$ .

Other imaging programmes applied to Kepler (and K2) candidates include adaptive optics imaging (Adams et al., 2012; Lillo-Box et al., 2012; Colón et al., 2012a; Lillo-Box et al., 2014a; Everett et al., 2015; Muirhead et al., 2015; Schmitt et al., 2016), speckle imaging (Howell et al., 2011; Schmitt et al., 2016), and lucky imaging (Lillo-Box et al., 2012).

A comparison of the various techniques is given by Lillo-Box et al. (2014a), and a comparison of the merits of high-contrast imaging versus spectroscopy as a probe of false-positives, blends, and close companions, is given by Teske et al. (2015a). The latter show the advantages of spectroscopic deblending techniques for very close-in companions ( $\theta \lesssim 0.02 - 0.05 \text{ arcsec}$ ), while high-contrast and speckle imaging can detect larger separation companions missed by spectroscopy.

- *Confirmation from induced variability:* This aims to identify non-transiting low-mass companions by detecting the photometric variability induced by the companion along its orbit, generated by Doppler beaming, tidal ellipsoidal distortion, or

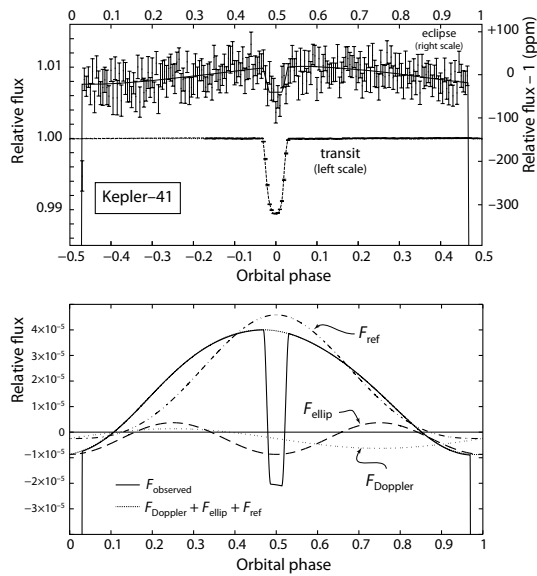


Figure 6.23: Top: data for Kepler-41 phased to the orbital period, and binned to 0.005 in phase. The lower data points are centred on the transit (scales at bottom and left), while the upper data points are centred on the occultation and magnified (scales at top and right). The fit to the eclipse data (solid curve) includes contributions from Doppler beaming, ellipsoidal variations, and reflected/emitted light. Bottom: best-fit model for Kepler-41 b phased to the orbital period and magnified to show the occultation. The full phase photometric model (dotted line) again includes Doppler beaming, ellipsoidal variations, and reflected/emitted light. From Quintana et al. (2013, Figures 2–3), by permission of IOP Publishing/AAS.

reflection/heating (§6.15.3). The method has been applied to Kepler-13 (Shporer et al., 2011), Kepler-41 as illustrated in Figure 6.23 (Quintana et al., 2013), Kepler-64 as illustrated in Figure 6.24 (Kostov et al., 2013), and Kepler-76 (Faigler et al., 2013). Quintana et al. (2013) estimated that some two dozen Kepler giant planets could be confirmed by this method.

- *Confirmation from Spitzer*: This appeals to the similarity between the Spitzer infrared and Kepler visible light transit signals to argue that the source is an orbiting planet rather than, for example, an unresolved background pair of orbiting stars. An upper limit of false-positive rate of 8.8% was derived from a sample of 51 candidates observed at  $4.5\ \mu\text{m}$  (Désert et al., 2015). Examples of individual applications include Kepler-10 c (Fressin et al., 2011), and CoRoT-7 b (Fressin et al., 2012a).

- *Confirmation from multi-planet statistics*: With the first two years of Kepler data, more than 2500 exoplanet candidates had been discovered, with  $\sim 40\%$  of those in multi-planet systems. The high rate of multiplicity combined with the low rate of identified false-positives suggests that the multi-planet systems must contain very few false-positives due to other systems not gravitationally bound to the target star. A series of three papers used these arguments to confirm several hundred Kepler candidates, with only a few false-positives expected between them (Lissauer et al., 2012b, 2014b; Rowe et al., 2014). Examples are given in Figure 6.25. The same arguments have been used for individual multi-planet systems, such as Kepler-33 (Lissauer et al., 2012b), and Kepler-65 (Chaplin et al., 2013).

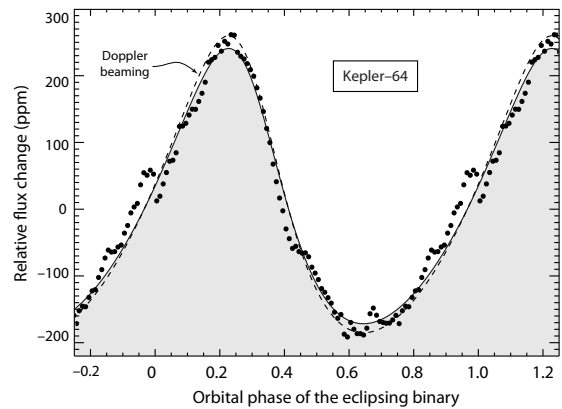


Figure 6.24: Doppler beaming of Kepler-64  $\equiv$  KIC-4862625. The relative normalised flux change is plotted with respect to the eclipsing binary’s orbital phase. The data binned in 0.01 intervals of phase (filled circles) approximately match the flux change estimated from Doppler beaming (dashed line) based upon the spectrum of the primary star and its spectroscopically-determined radial velocity curve. The amplitude of the best-fitting curve (solid line) is  $93 \pm 1.7\%$  that of the estimate (dashed line). From Kostov et al. (2013, Figure 8), by permission of IOP Publishing/AAS.

The relative transit durations of planets present in the same light curve is a further metric that can be used to validate them as planets around the same host star (Lissauer et al., 2012b).

- *Confirmation from dynamical stability*: For the 16-month data release, Fabrycky et al. (2014) assessed the fidelity of the multi-planet candidates based on the apparent orbital stability of almost all of the systems. They also found that the candidates avoid close orbital spacings that would lead to instability, and concluded that 85–99% of the candidate pairs are real systems.
- *Confirmation from transit time variations*: Multi-planet systems which show correlated transit timing variations are generally considered as confirmed planetary systems. Further details are given in Section 6.20.
- *Confirmation from colour signature*: Use of multicolour photometry to reject false-positives was noted in early discussions of the method (Rosenblatt, 1971). It exploits an integrated colour which evolves through the transit due to the changing projection of the occulting planet onto the differentially limb-darkened stellar disk (which is more centrally concentrated in blue light). Small bodies produce a signature that is distinct from grazing eclipsing binaries, triple systems, and blends, and from which  $R_p/R_*$  can be estimated (Tingley, 2004).

The technique cannot distinguish between transiting bodies that have similar radii to giant exoplanets, such as extremely late red dwarfs and brown dwarfs. Consequently, planets that are smaller than the smallest brown dwarfs (i.e. smaller than Saturn, e.g. Burrows et al. 2011) can be confirmed using only their colour signature, while those that are larger require a mass limit from radial velocity for confirmation. Multicolour photometry can also reveal unknown stellar neighbours and binary companions that do not affect the classification of the transiting object, but which can affect the estimated planetary radius.

Tingley et al. (2014) developed and applied the method to Kepler-418 b using multicolour photometry from GranTeCan, and corroborated by radial velocities with NOT-FIES.

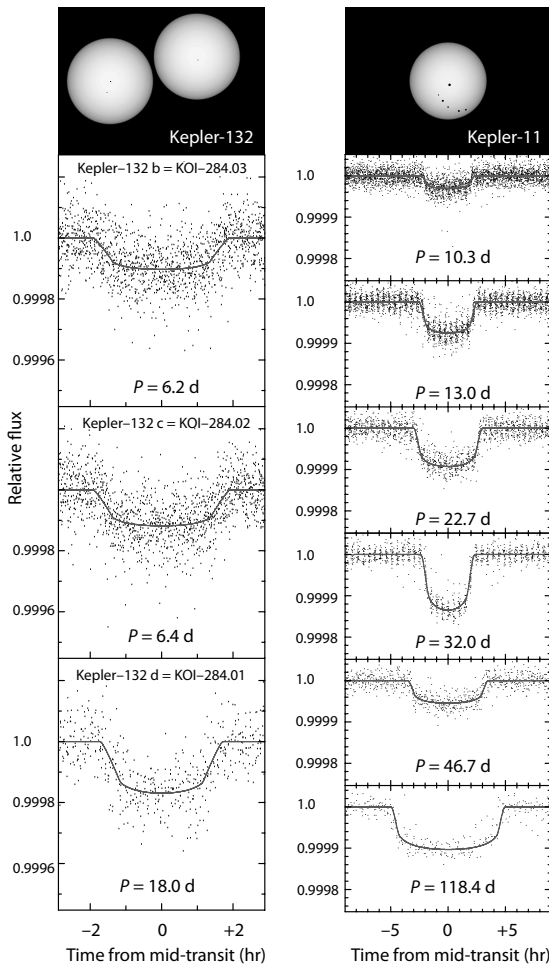


Figure 6.25: Left: transits of the three planets in the Kepler-132 binary system. The upper panel shows the star and planet sizes at a uniform scale, with the planet distance below the middle of the star corresponding to the transit impact parameter. The lower panels show the detrended flux phased at the period of each transiting planet signal (and with the best-fit model for the other two planet candidates removed), in order of increasing period. Dots represent the individual long-cadence observations. Right: similar diagram for the 6-planet system Kepler-11. From Lissauer et al. (2014b, Figures 3–7a), by permission of IOP Publishing/AAS.

- *Confirmation from chromospheric emission:* From the statistics of chromospheric emission from confirmed giant planet systems and eclipsing binary stars, Karoff et al. (2016) suggested that giant planet candidate systems with chromospheric emission stronger than the Sun are not giant-planet systems, but false-positives perhaps due to tidally-interacting binaries with strong chromospheric emission.
- *Confirmation from stellar density:* At least two pairs of planets in candidate multiple systems were found to be particularly closely spaced: Kepler-132 (KOI-284) with  $P_1/P_2 = 1.038$  (Lissauer et al., 2011b) and KOI-2284 with  $P_1/P_2 = 1.065$  (Fabrycky et al., 2014). Due to their separation in terms of Hill radii, neither system is likely to be stable. An alternative explanation is

that the two planets in each system orbit different members of a wide binary star (Lissauer et al., 2012b, 2014b).

Transit durations for circular orbits being governed by the mean stellar density (Seager & Mallén-Ornelas, 2003), the ratio of the orbital-velocity normalised transit durations provides an associated diagnostic (Steffen et al., 2010; Fabrycky et al., 2014)

$$\xi \equiv \frac{t_{T,1}/P_1^{1/3}}{t_{T,2}/P_2^{1/3}}, \quad (6.7)$$

where  $t_T$  is the transit duration, and subscripts 1,2 denote the inner and outer planets. If  $\xi$  is near unity, it implies that the planets are orbiting stars of roughly equal density, if not the same star. For the unstable pairs in Kepler-132 (KOI-284) and KOI-2248, the values of  $\xi$  are 0.96 and 0.97 respectively, i.e. failing to give evidence of the pairs orbiting different stars.

At the same time, if the planets are orbiting different stars in a physical binary, then the two stars may be similar and resolvable with high resolution imaging, as already achieved for Kepler-132 (Lissauer et al., 2012b).

### 6.13 Transit light curves

Figure 6.26 is a schematic of an orbiting planet showing, progressively, the transit of the planet as it passes in front of the star, the subsequent rise in flux as the planet's illuminated surface comes into view, and the drop in flux during the secondary eclipse as the planet passes behind the star.

The problem of constructing theoretical transit light curves, and using them to infer properties of the transiting planet–star system, appears simple enough in principle. One projected sphere (that of the planet) passes across another (the star) and the light from the star is attenuated according to the fraction of the two surfaces which overlap. In practice, algebraic treatment of the basic problem of two overlapping circles is unwieldy. Including the effects of stellar limb darkening, light reflected from the planet, blending due to background objects, and effects due to orbit eccentricity and other higher-order terms, conspire to make the problem a challenging one, yet rich in the physical information that the transit light curves convey.

As the field has progressed over the past decade, observation and interpretation has moved rapidly beyond simply the photometric detection of the transit, to include multicolour photometry and spectroscopy during the transit and secondary eclipse phases, and searches for detailed photometric structure, transit time variations, and reflected light during day-side illumination.

#### 6.13.1 Principal transit observables

There are four principal observables which characterise the duration and profile of the primary transit: the period  $P$ , the transit depth  $\Delta F$ , the interval between the first and fourth contacts  $t_T$ , and the interval between the second and third contacts  $t_F$  (see Figure 6.26).

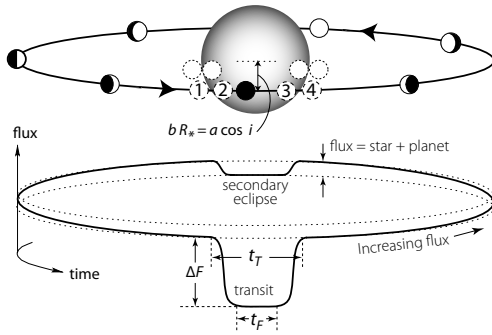


Figure 6.26: Schematic of a transit. During the transit, the planet blocks a fraction of the star light. After the transit, the planet's brighter day-side progressively comes into view, and the total flux rises. It drops again during the secondary eclipse as the planet passes behind the star. Dashed circles show first to fourth contact points; those for smaller impact parameter (dotted) are more closely separated in time, and the ingress/egress slopes correspondingly steeper. The total transit duration  $t_T$  is between first and fourth contact, while  $t_F$  is timed between second and third contact. After Winn (2009, Figure 1).

From these, three geometrical equations together describe the principal features of the transit light curve (Seager & Mallén-Ornelas, 2003, eqn 1–3): the transit depth  $\Delta F$  itself, the total transit duration  $t_T$ , and the transit shape specified by the ratio of the flat (fully occulted) part to the total transit duration  $t_F/t_T$  which, for circular orbits, are

$$\Delta F \approx \left(\frac{R_p}{R_\star}\right)^2 \quad (6.8)$$

$$\sin(t_T \pi / P) = \frac{R_\star}{a} \left\{ \frac{[1 + (R_p/R_\star)]^2 - [(a/R_\star) \cos i]^2}{1 - \cos^2 i} \right\}^{1/2} \quad (6.9)$$

$$\frac{\sin(t_F \pi / P)}{\sin(t_T \pi / P)} = \frac{\left\{ [1 - (R_p/R_\star)]^2 - [(a/R_\star) \cos i]^2 \right\}^{1/2}}{\left\{ [1 + (R_p/R_\star)]^2 - [(a/R_\star) \cos i]^2 \right\}^{1/2}} \quad (6.10)$$

The first follows from the ratio of the areas of the projected disks of the planet and star. The total transit time follows from the fraction of the orbital period  $P$  during which the projected distance between the centres of the star and planet is less than the sum of their radii (see Figure 6.26). The transit shape is derived similarly.

In the simplest interpretation, if  $R_\star$  can be estimated from, say, spectral classification, then  $R_p$  can be estimated from Equation 6.8. Setting  $i = 90^\circ$ ,  $b = 0$ , the duration of the transit for a circular orbit is numerically

$$t_T \approx 13 \left(\frac{M_\star}{M_\odot}\right)^{-1/2} \left(\frac{a}{1 \text{ au}}\right)^{1/2} \left(\frac{R_\star}{R_\odot}\right) \text{ hours}, \quad (6.11)$$

giving  $t_T \sim 25$  h for a Jupiter-type orbit and 13 h for an Earth-type. The minimum inclination where transits can occur is given by  $\cos i_{\min} = (R_\star/a)$ , while grazing incidence transits occur for  $a \cos i = (R_\star \pm R_p)$ .

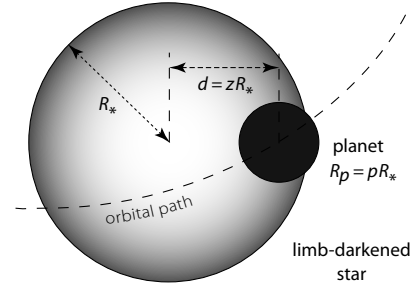


Figure 6.27: Schematic for the derivation of the theoretical light curve, showing the instantaneous transit geometry as viewed by the observer, and the definition of the parameters  $p = R_p/R_\star$  and  $z = d/R_\star$ . Limb-darkening blurs the boundary between transit ingress and egress. After Mandel & Agol (2002, Figure 1), by permission of IOP Publishing/AAS.

### 6.13.2 Geometric formulation

The formulation of Mandel & Agol (2002), in terms of the geometry of overlapping circles (see also Kopal, 1975), provides an insight into observed transit light curves. They develop an expression for the ratio of obscured to unobscured flux,  $F(p, z) = 1 - \lambda(p, z)$ , in terms of  $p = R_p/R_\star$  and  $z = d/R_\star$ , where  $R_p$  is the planet radius,  $R_\star$  is the stellar radius, and  $d$  is the distance between star and planet centres (Figure 6.27).

For a uniform source, i.e. without limb darkening, there are three geometrical regimes, handled separately. Outside of transit ( $1 + p < z$ ) there is no attenuation and  $\lambda(p, z) = 0$ . Within the fully occulted region ( $z \leq 1 - p$ ) the attenuation is simply the ratio of the projected areas,  $\lambda(p, z) = p^2$ . For the partially overlapping region, and determined only by geometry,

$$\lambda(p, z) = \frac{1}{\pi} \left[ p^2 \kappa_0 + \kappa_1 - \sqrt{\frac{4z^2 - (1 + z^2 - p^2)^2}{4}} \right], \quad (6.12)$$

$$\text{where } \kappa_0 = \cos^{-1}[(p^2 + z^2 - 1)/2pz],$$

$$\text{and } \kappa_1 = \cos^{-1}[(1 - p^2 + z^2)/2z].$$

The limb-darkened light curve is given by

$$F(p, z) = \left[ \int_0^1 I(r) 2r dr \right]^{-1} \int_0^1 I(r) dr \frac{d \left[ F\left(\frac{p}{r}, \frac{z}{r}\right) r^2 \right]}{dr}. \quad (6.13)$$

Expressions for  $F(p, z)$  in the presence of limb darkening depend on the region of  $(p, z)$  parameter space, for example whether the planet is crossing the limb, the centre of the disk, or (in theory) both. Theoretical light curves which include limb darkening (e.g. Mandel & Agol, 2002; Seager & Mallén-Ornelas, 2003) show that its effects are threefold: changing the transit depth  $\Delta F$  as a function of impact parameter; making the bottom rounder (and hence the flat part shorter, reducing  $t_F$ ); and blurring the boundary between ingress/egress and the flat bottom (Figure 6.28).

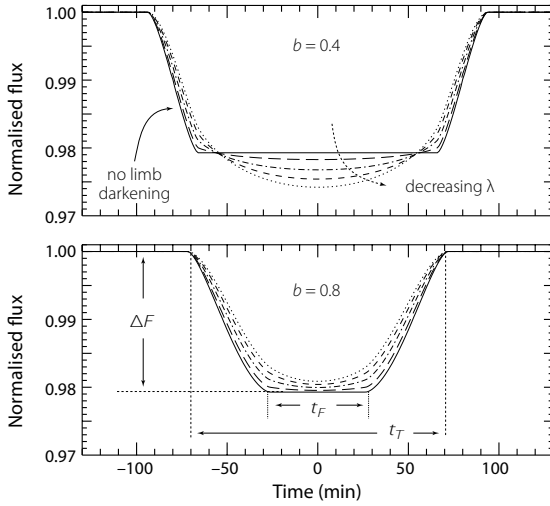


Figure 6.28: Theoretical transit curves for two impact parameters  $b$ , without (solid curves) and with (solar-type) limb darkening at 3, 0.8, 0.55 and  $0.45 \mu\text{m}$  (effects increase towards shorter wavelength). Model parameters are:  $R_p = 1.4R_J$ ,  $a = 0.05 \text{ au}$ ,  $R_\star = R_\odot$ ,  $M_\star = M_\odot$ . From Seager & Mallén-Ornelas (2003, Figure 11), by permission of IOP Publishing/AAS.

For small  $R_p$ , the description of the fully occulted part of the light curve can be simplified by assuming that the surface brightness of the star is constant under the disk of the planet. For  $p \leq 0.1$  and  $1 - p < z < 1 + p$  an approximation, accurate to  $\sim 2\%$ , is then (their eqn 8)

$$F = 1 - \frac{1}{4\Omega(1-a)} \int_{z-p}^1 I(r) 2r dr \left( p^2 \cos^{-1} \left[ \frac{z-1}{p} \right] - (z-1) \sqrt{p^2 - (z-1)^2} \right), \quad (6.14)$$

where  $\Omega = \sum c_n(n+4)^{-1}$ . To determine  $z(t)$  requires the planetary orbit parameters, which for  $e = 0$  is given by  $z(t) = aR_\star^{-1} [(\sin \omega t)^2 + (\cos i \cos \omega t)^2]^{1/2}$ , where  $\omega$  is the orbital frequency.

Their routines for computing transit light curves, for arbitrary limb-darkening (e.g., according to spectral type), are frequently used for transit modeling. Pál (2008) derived partial derivatives of these functions for the case of quadratic limb darkening, useful for model fitting. He also compared the statistical errors in the light curve parameters as a function of the observing bandpass, from the near-ultraviolet to mid-infrared.

**Methods from eclipsing binaries** Synthetic light curve codes, developed for the analysis of eclipsing binaries, have been adapted and used to study planetary transits. Thus EBOP (Etzel, 1993) is based on a geometrical solution for biaxial ellipsoids (so accounting for tidal deformations from spherical shape), but originally considered only a linear law of limb darkening.

Modifications to take account of non-linear limb darkening were made by Giménez & Diaz-Cordovés

(1993) and, more recently, developed for the analysis of exoplanet light curves, including error analysis, by Southworth et al. (2004, 2007).

A somewhat similar numerical approach building on the sequence of discrete geometries and specific limb darkening introduced by Mandel & Agol (2002) was developed by Giménez (2006a). This is based on the work of Kopal (1977) who, also in the context of close binary systems, used the mathematics of physical optics to express the loss of light during mutual eclipses as a cross-correlation of two circular apertures representing the eclipsing and eclipsed disks. The approach can be generalised to eccentric orbits, arbitrary limb-darkening expressions, and non-zero luminosity of the planet.

The fractional loss of light as a function of orbital phase is first expressed as

$$\alpha(\theta) = \sum_{n=0}^N C_n \alpha_n, \quad (6.15)$$

where the coefficients  $C_n$  are related to the terms in a general law of limb darkening (cf. Equation 6.67)

$$I(\mu) = 1 - \sum_{n=1}^N u_n (1 - \mu^n), \quad (6.16)$$

such that the geometrical and limb darkening parameters are decoupled.

The  $\alpha_n$  are formulated, as in Mandel & Agol (2002), in terms of the apparent separation between the centres of the projected disks of the star and planet  $d$  as

$$\alpha_n(b, c) = \frac{b^2(1-c^2)^{v+1}}{v\Gamma(v+1)} \sum_{j=0}^{\infty} (-1)^j (2j+v+2) \frac{\Gamma(v+j+1)}{\Gamma(j+2)} \times \left\{ G_j(v+2, v+1; 1-b) \right\}^2 G_j(v+2, 1; c^2), \quad (6.17)$$

where  $b \equiv R_p/(R_\star + R_p)$ ,  $c \equiv d/(R_\star + R_p)$ , and  $v \equiv (n+2)/2$ ;  $\Gamma$  is the gamma function, and  $G_n(p, q; x)$  are the Jacobi–Gegenbauer polynomials.

Generating the light curve thus involves defining  $I(\mu)$ , stepping through orbit phase to determine the instantaneous star–planet projected separation  $d$  through numerical integration of Kepler’s equation, then evaluating the  $\alpha_n$  using this convergent series to the desired accuracy (e.g. to  $j \approx 20$  for a geometric precision better than  $5 \times 10^{-5}$ ).

The light curve synthesis code ELC, making use of the NextGen model atmospheres (Orosz & Hauschildt, 2000), has been applied, amongst others, to the ellipsoidal variations observed in the Kepler light curve of HAT-P-7 (§6.14; Welsh et al., 2010). An upgraded ‘photodynamical’ version, allowing for dynamics instead of Keplerian kinematics, is described in the context of the circumbinary Kepler-453 by Welsh et al. (2015).

### 6.13.3 Light curve fitting

The inverse problem, that of establishing the appropriate physical parameters (and limb darkening coefficients) for a given light curve, proceeds through a  $\chi^2$  search for the unknowns through some appropriate region of parameter space, seeded by first-order estimates of the relative planetary radius ( $R_p/R_*$ ), the impact parameter ( $b \equiv a \cos i/R_*$ ), and the normalised separation between star and planet ( $a/R_*$ ).

Efficient numerical minimisation schemes, such as the Bayesian-based Markov Chain Monte Carlo algorithm, which also provides the full multi-dimensional joint probability distribution for all the parameters, or the Levenberg–Marquardt acceleration (Press et al., 2007), can be adopted, essentially providing confidence levels determined by surfaces of constant  $\chi^2$ . For practical examples see, e.g., Winn et al. (2007c).

Figure 6.29 shows a number of examples of transit light curves, illustrating the actual ratios of planet and star radii, and a schematic of the impact parameter derived from the light curve analysis.

### 6.13.4 Biases

Kipping & Sandford (2016) have emphasised that the transit method is inherently biased due to both geometric and detection-driven effects. These include the bias of impact parameter towards near-equatorial geometries, the various biases related to the observation of planets transiting near pericentre, and that of the ratio-of-radii,  $R_p/R_*$ , driven by an enhanced geometric transit probability and modestly longer durations. The bias in mass determination from transit timing variations is discussed by Steffen (2016).

Undetected stellar companions can bias the derived radii for transiting planets: for KOI hosts assumed to be single, the presence of a companion star can lead to planetary radii underestimated by a factor 1.5, reducing to 1.2 if companions are excluded from typical radial velocity and high-resolution imaging observations (Ciardi et al., 2015a; Furlan & Howell, 2017; Hirsch et al., 2017). Statistics such as the inferred occurrence rates of Earth-size planets will be affected.

Other biases follow from the unrecognised presence of more complex astrophysical environments such as moons and rings.

### 6.13.5 Circular orbits

Various physical parameters can be extracted from the light curves, according to the accuracy and type of observation (e.g. whether the secondary eclipse is observed), the assumptions made (e.g. of a circular orbit, and use of Kepler's law), information about the orbit available from other sources (e.g. radial velocity or astrometry), and astrophysical assumptions (such as the mass–luminosity relation for the primary star).

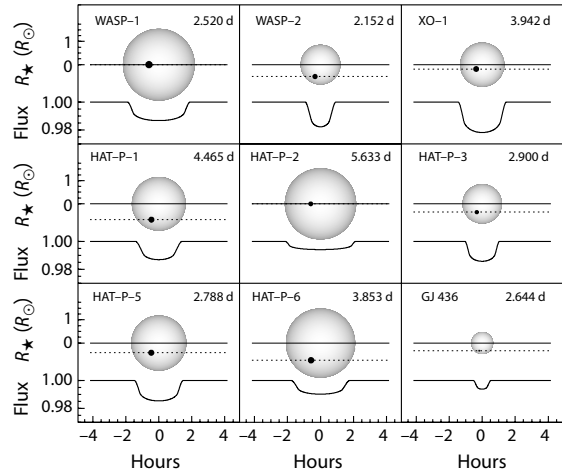


Figure 6.29: Examples of transit light curves, on a uniform time and relative flux scale. Planet and star sizes are also shown to scale, with the transit depth proportional to the ratio of their projected areas. Planet trajectories are shown as dotted lines, according to their estimated impact parameters. From Torres et al. (2008, Figure 8), by permission of IOP Publishing/AAS.

There is a unique and exact solution of the planet and star parameters which can be obtained from a transit light curve with two or more transits, under the assumptions of a circular orbit, for observations in a (long wavelength) bandpass where limb darkening is negligible, and ignoring possible contributions of contaminating (blended) sources. This outline follows the development of Seager & Mallén-Ornelas (2003).

From the three geometrical equations describing the light curve (Equations 6.8–6.10), three dimensionless combinations can be constructed: the planet–star radius ratio directly from Equation 6.8

$$\frac{R_p}{R_*} = \sqrt{\Delta F}; \quad (6.18)$$

the impact parameter  $b$ , defined geometrically as the projected distance between the planet and star centres during mid-transit in units of  $R_*$  (Figure 6.26)

$$b \equiv \frac{a}{R_*} \cos i = \left\{ \frac{(1 - \sqrt{\Delta F})^2 - \frac{\sin^2(t_T \pi / P)}{\sin^2(t_1 \pi / P)} (1 + \sqrt{\Delta F})^2}{1 - [\sin^2(t_T \pi / P) / \sin^2(t_1 \pi / P)]} \right\}^{1/2}; \quad (6.19)$$

and the ratio  $a/R_*$

$$\frac{a}{R_*} = \left\{ \frac{(1 + \sqrt{\Delta F})^2 - b^2 [1 - \sin^2(t_T \pi / P)]}{\sin^2(t_T \pi / P)} \right\}^{1/2}. \quad (6.20)$$

Additionally invoking Kepler's third law

$$P^2 = \frac{4\pi^2 a^3}{G(M_* + M_p)} \quad (6.21)$$

to set the physical length scale, an expression for the stellar density  $\rho_\star$  can be derived from Equation 6.20, assuming  $M_p \ll M_\star$ ,

$$\rho_\star \equiv \frac{M_\star}{R_\star^3} \quad (6.22)$$

$$= \left( \frac{4\pi^2}{P^2 G} \right) \left\{ \frac{(1 + \sqrt{\Delta F})^2 - b^2 [1 - \sin^2(t_T \pi / P)]}{\sin^2(t_T \pi / P)} \right\}^{3/2}$$

Uniqueness can be imposed on the dimensionless ratios by also invoking the stellar mass–radius relation

$$R_\star = k M_\star^x, \quad (6.23)$$

where  $k$  is a constant, distinct for main sequence or giants, and  $x$  is the corresponding power law.

The five physical parameters  $R_\star$ ,  $M_\star$ ,  $i$ ,  $a$ , and  $R_p$  are then (Seager & Mallén-Ornelas, 2003, eqn 10–14)

$$\frac{M_\star}{M_\odot} = \left( k^3 \frac{\rho_\star}{\rho_\odot} \right)^{1/(1-3x)}, \quad (6.24)$$

$$\frac{R_\star}{R_\odot} = k \left( \frac{M_\star}{M_\odot} \right)^x = \left( k^{1/x} \frac{\rho_\star}{\rho_\odot} \right)^{x/(1-3x)}, \quad (6.25)$$

$$a = \left( \frac{P^2 G M_\star}{4\pi^2} \right)^{1/3}, \quad (6.26)$$

$$i = \cos^{-1} \left( b \frac{R_\star}{a} \right), \quad (6.27)$$

$$\frac{R_p}{R_\odot} = \frac{R_\star}{R_\odot} \sqrt{\Delta F} = \left( k^{1/x} \frac{\rho_\star}{\rho_\odot} \right)^{x/(1-3x)} \sqrt{\Delta F}. \quad (6.28)$$

For main sequence stars  $k = 1$  and  $x \approx 0.8$  (Cox, 2000, pp355–357), and  $(R_p/R_\odot) = (\rho_\star/\rho_\odot)^{-0.57} \sqrt{\Delta F}$ .

With the further approximation  $R_\star \ll a$ , equivalent to  $t_T \pi / P \ll 1$ , the expressions for  $b$ ,  $a$ ,  $\rho_\star$  simplify to

$$b = \left\{ \frac{(1 - \sqrt{\Delta F})^2 - (t_F/t_T)^2 (1 + \sqrt{\Delta F})^2}{1 - (t_F/t_T)^2} \right\}^{1/2}, \quad (6.29)$$

$$\frac{a}{R_\star} = \frac{2P}{\pi} \Delta F^{1/4} \left( t_T^2 - t_F^2 \right)^{-1/2}, \quad (6.30)$$

$$\rho_\star = \frac{32P}{G\pi} \Delta F^{3/4} \left( t_T^2 - t_F^2 \right)^{-3/2}. \quad (6.31)$$

Uniqueness of this solution allows first-order physical parameter estimates to be made from the transit light curve measurements alone, including  $\rho_\star$  (Equation 6.22) and hence  $R_p$  (Equation 6.28). If  $\rho_\star$  implies that the star is a giant, the companion may immediately be identified as a more massive object of lesser interest.

If  $M_\star$  and  $R_\star$  are assumed known from the spectral type, then the problem is over-constrained, and Equation 6.31 can be re-arranged to give an expression for the orbital period, even if only a single transit is observed

$$P = \frac{G\pi}{32} \frac{M_\star}{R_\star^3} \frac{(t_T^2 - t_F^2)^{3/2}}{\Delta F^{3/4}}. \quad (6.32)$$

For  $P$  in days,  $G\pi/32 = 288.73$ . Seager & Mallén-Ornelas (2003) estimate that  $P$  can be determined in this way to  $\sim 15 - 20\%$  for  $\delta t < 5$  min and  $\sigma \sim 0.0025$  mag.

Carter et al. (2008) derived analytic approximations for the corresponding uncertainties and covariances.

### 6.13.6 Eccentric orbits

In cases where eccentricities can be estimated, a significant fraction of transiting planets (especially in single planet systems) have non-zero eccentricities (§6.26.2). The assumption of a circular orbit, which underlies the formulation of Seager & Mallén-Ornelas (2003), is therefore frequently an oversimplification.

**Light curves** Some lengthy algebra leads to the equations defining a general 3d elliptical orbit, and thereafter to prescriptions for the corresponding light curve features,  $P$ ,  $R_p/R_\star$ ,  $t_T$ , and  $t_F$  (Kipping, 2008, Appendix A). These reduce to the results of Seager & Mallén-Ornelas (2003) for  $e = 0$  (cf. the models of Tingley & Sackett 2005 and Ford et al. 2008a). Of the seven variables which can be adjusted to produce a light curve with the same four primary features,  $e$  and  $\omega$  (as well as  $M_\star$ ) cannot be determined from the transit light curve alone.

**Transit duration** Under the same assumption that  $R_p \ll R_\star \ll a$ , the transit duration is much less than the orbital period, and the planet–star separation during the transit is nearly constant. Ford et al. (2008a) derived an expression for the total transit duration for an eccentric orbit (cf. Equation 6.9)

$$\frac{t_T}{P} \approx \frac{R_\star}{\pi a \sqrt{1 - e^2}} \left\{ \left( 1 + \frac{R_p}{R_\star} \right)^2 - b^2 \right\}^{1/2} \left( \frac{r_t}{a} \right), \quad (6.33)$$

where  $r_t$  is the planet–star separation at time of mid-transit

$$r_t = a(1 - e \cos E_t) = \frac{a(1 - e^2)}{1 + e \cos \nu_t} = \frac{a(1 - e^2)}{1 + e \cos \omega}, \quad (6.34)$$

where  $\nu_t$  and  $E_t$  are the true and eccentric anomalies at the time of transit, and  $\omega$  the argument of pericentre. The ratio of the transit duration to that of a planet on an equivalent circular orbit is then  $(1 + e \cos \omega)/(1 - e^2)^{1/2}$ . This is dependent on  $e$  and  $\omega$ , being less than unity for planets that transit near pericentre, and greater than unity for those transiting near apocentre. For highly eccentric orbits (say,  $e = 0.9$ ), the ratio can range between  $\sim 0.2 - 4$ . It follows that estimates of  $R_p$  will be biased if scaled to  $R_\star$  which is itself derived from the transit light curve on the erroneous assumption of a circular orbit.

An example of such a bias is given by Kipping (2008): from Spitzer timing measurements for HD 209458 (Richardson et al., 2006), and an estimate of  $e = 0.014$  (Winn et al., 2005), he found a 1% larger value for  $R_p$

from the transit timing analysis than under the assumption  $e = 0$ . A more robust procedure for light-curve fitting is therefore to use measurements independent of the transit to determine  $M_*$ ,  $M_p$ ,  $e$ , and  $\omega$  (and to invoke stellar evolution if no measure of  $M_*$  is available) and then use the transit observations to determine  $P$ ,  $R_*$ , and finally  $R_p$  once  $e$  is known.

**Light curve asymmetry** Barnes (2007a) and Kipping (2008) quantified the light curve asymmetry as a function of  $e$ . On an elliptical orbit, and unless the planet is at pericentre or apocentre at the time of mid-transit, the planet's azimuthal velocity will change between ingress and egress: if the transit occurs after pericentre and before apocentre, the ingress time will be shorter than egress, and *vice versa*. The ingress and egress durations are given by (Barnes, 2007a, eqn 19)

$$\tau = \frac{R_p}{v_v \cos(\sin^{-1} b)}, \quad (6.35)$$

$$\text{where } v_v = v_0 \frac{1 + e \cos f}{\sqrt{1 - e^2}}. \quad (6.36)$$

Here,  $v_v$  is the planet's azimuthal velocity at the position in the orbit corresponding to the true anomaly  $v$ ,  $v_0$  the equivalent velocity for a circular orbit with the same semi-major axis, and  $b$  is the impact parameter.

HAT-P-2 b (HD 147506) has a particularly favourable geometry with true anomaly at mid-transit close to  $v = \pi/2$ , and yields  $\tau_{\text{ingress}} = 636$  s and  $\tau_{\text{egress}} = 517$  s (Figure 6.30). In general, while mid-transit times can be shifted from seconds to minutes depending on  $e$ , it will be a challenge to distinguish different eccentricities from the difference in ingress and egress shapes, or ingress and egress durations, even in the infrared where the effects of limb darkening are minimised.

**Transit probability** Although an eccentric planet spends the majority of its *time* at distances from the star larger than its semi-major axis, the majority of its true anomaly (§2.1.1) is spent at smaller distances. This results in a larger fraction of the celestial sphere being intercepted by the planet's shadow, and a higher probability that the planet will transit than for a corresponding circular orbit, although the time spent in transit at these locations will be shorter (Figure 6.31).

For the more general case of an elliptical orbit, a transit requires  $\omega + v = \pi/2$  (Kane, 2007), and the geometric transit and eclipse probabilities (cf. Equation 6.1) are inversely proportional to the star-planet separation at the time when the planet crosses the star-observer plane perpendicular to the plane of the planetary orbit.

From the expression for the star-planet distance as a function of  $v$  (Equation 2.15), the geometric transit probability can be expressed as

$$p = \frac{(R_* \pm R_p)(1 + e \cos(\pi/2 - \omega))}{a(1 - e^2)}, \quad (6.37)$$

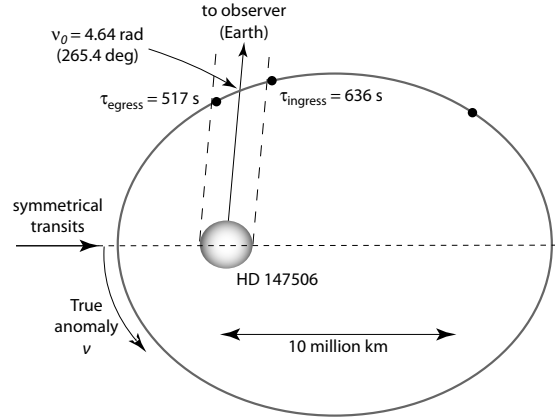


Figure 6.30: Schematic of the orbit of HAT-P-2 (HD 147506). As viewed from Earth, the transit occurs at a value of the true anomaly  $v_0 = 4.64$  rad (close to  $-90^\circ$ ), such that the asymmetry between ingress and egress is close to its maximum. If the transit were to be viewed at  $v = 0$  or  $v = \pi$  (i.e. from the left or right in the figure), the transit would be symmetrical. From Barnes (2007a, Figure 5), reproduced by permission, Institute of Physics Publishing.

where inclusion of the (generally small) term  $\pm R_p$  excludes or includes grazing transits. This is valid for all  $e$ , and independent of  $i$ . As evident from the schematic of Figure 6.31, the transit probability is sensitive to the argument of pericentre,  $\omega$  (Kane et al., 2012b).

Integrating over the extent of the planet's shadow for all values of (the *a priori* unknown)  $\omega$  (cf. Barnes, 2007a, eqn 1–8) leads to the transit probability for planets on eccentric orbits

$$p = \left( \frac{R_* \pm R_p}{a} \right) \left( \frac{1}{1 - e^2} \right). \quad (6.38)$$

This reduces to Equation 6.1 for  $e = 0$  and  $R_p \ll R_*$ , and shows that planets on eccentric orbits are more likely to transit than those in circular orbits with the same semi-major axis, by a factor  $(1 - e^2)^{-1}$ .

For a circular orbit, the geometric conditions for transits and secondary eclipses are identical, while for eccentric orbits an observer may see transits without a secondary eclipse, and *vice versa*.

**Probability of secondary eclipses** For an isotropic distribution of elliptical orbit orientations, the geometric probability of *at least one* of the components being eclipsed is given by (Dong et al., 2013b, §4.1)

$$p_1 = (R_* + R_p) \frac{1 + 2e/\pi}{a(1 - e^2)} \quad \text{for } (R_* + R_p) \ll a. \quad (6.39)$$

The probability of observing *both* eclipses is given by

$$p_2 = \frac{\pi - 2e}{\pi + 2e} p_1, \quad (6.40)$$



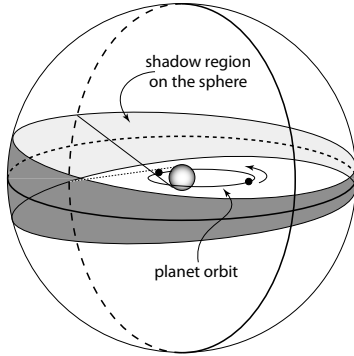


Figure 6.31: Geometry of an eccentric planetary orbit, and the area of the celestial sphere onto which the transit is projected. At pericentre (planet at left in the figure) the region is larger than when the planet is at apocentre. Similar considerations for a circular orbit lead to the transit probability given by Equation 6.1. Adapted from Barnes (2007a, Figure 1).

with  $p_2 \rightarrow 0.22p_1$  as  $e \rightarrow 1$ . The timing difference between the eclipses is

$$\Delta t = \frac{P}{\pi} \left[ \arccos \left( \frac{e \cos \omega}{\sqrt{1 - e^2 \sin^2 \omega}} \right) - \frac{\sqrt{1 - e^2} e \cos \omega}{1 - e^2 \sin^2 \omega} \right], \quad (6.41)$$

where  $\omega$  is the argument of pericentre.

At high  $e$  the eclipses are most likely to occur near pericentre, and the separation between the two eclipses is of order the pericentre passage time  $\sim P(1 - e)^{3/2}/2$ . The separation reaches a minimum at  $\omega = 0$ , given by

$$\Delta t = \frac{P}{\pi} (\arccos e - e\sqrt{1 - e^2}). \quad (6.42)$$

As  $e \rightarrow 1$ ,  $\Delta t \rightarrow 2P_f/3\pi$ , and  $\Delta t \sim P(1 - e)^{3/2}/2$  to an accuracy of better than 20%.

The eccentricity of the orbit can be determined by radial velocity measurements, while lower limits on  $e$  are given by the timing separation between the two eclipses.

It is the form of these equations that frequently leads to constraints on the combination  $e \cos \omega$ , e.g. for HAT-P-6, HAT-P-8, and XO-4 (Todorov et al., 2012).

**Implications for transit surveys** The implication for transit surveys is two-fold (Burke, 2008): an increase in the probability for the planet to generate transits near pericentre, accompanied by a corresponding reduction in the detectability due to a shorter transit duration. For an eccentricity distribution matching known planets with  $P > 10$  d, the probability of transits is  $\approx 1.25$  times higher than the equivalent circular orbit and the average transit duration is  $\approx 0.88$  times shorter. These two opposing effects nearly cancel for a realistic transit survey.

There is a similar consequence for efforts to detect transits in planets discovered by radial velocity measures: the transit probability for any given planet is not a strictly declining function of  $a$ , but depends on a favourable combination of  $e$  and  $\omega$  (Seagroves et al., 2003; Kane & von Braun, 2008).

One of the highest *a priori* transit probabilities considered by Seagroves et al. (2003) belonged not to one of the short-period hot Jupiters, which tend to average transit probabilities of  $\sim 12\%$ , but to the  $P = 550$ -d HIP 75458 b (*t Dra*). Here, the large semi-major axis (1.34 au) is compensated by the large  $R_\star = 12.8R_\odot$ , and favourable orbital geometry ( $e = 0.7$ ,  $\omega = 94^\circ$ ), leading to an *a priori* transit probability of 15%. Although this planet does not, in fact, transit, similar arguments led to the search for and successful detection of transits for the  $P = 21$ -d HD 17156 b, and the  $P = 111$ -d HD 80606 b (§6.3.1).

More detailed considerations of transit probabilities should take account not only of the prior probability distribution of  $i$  but also of the prior probability distribution of the companion mass  $M_c$ . Stevens & Gaudi (2013) give analytic expressions for the posterior transit probability assuming a power-law form for the distribution of true masses with exponent  $\alpha$ . For low transit probabilities, these probabilities reduce to a constant multiplicative factor of the corresponding prior transit probability. The prior and posterior probabilities are equal for  $\alpha = -1$ , whereas the posterior transit probability is larger for  $\alpha < -1$ , less than the prior for  $\alpha \geq 0$ , and can be arbitrarily small for  $\alpha > 1$  (with associated implications for optimum targets from radial velocity-detected planets).

**Stellar inclination constraints** Blind transit surveys have very low yields because of the rapid fall off in transit probability for increasing semi-major axes. Transit probabilities can be improved by constraining the inclination of the stellar rotation axes in advance. Beatty & Seager (2010) performed simulations for co-planar and misaligned systems, and found that stellar inclination constraints (from spectroscopy or asteroseismology) can improve the transit probability by almost an order of magnitude for habitable-zone planets. Herrero et al. (2012) derived similar constraints from the relationship between stellar activity and rotational velocity for GKM dwarfs, finding an increased transit probability for stars inferred to be ‘equator on’ by a factor 2–3 compared with a general search without pre-selection.

### 6.13.7 Physical quantities

Apart from the stellar density  $\rho_\star$  noted above, and planet’s surface gravity  $\log g_p$  detailed below, the primary stellar parameters ( $M_\star$ ,  $R_\star$ ,  $\log g_\star$ ,  $\rho_\star$ , and age), as well as the absolute planet parameters (as opposed to their ratios in terms of the stellar parameters), must appeal to the use of stellar evolutionary models. A variety of models exist in the literature, which provide generally consistent results, especially over the regions of intermediate stellar mass and solar metallicity.

Combining high accuracy transit observations with such stellar evolutionary models, yields transit parameters, stellar parameters, and derived planet parameters. An example of the accuracy achieved from transit observations is shown in Table 6.1 for the case of WASP-52.

**Stellar density** The stellar density  $\rho_\star$  estimate which can be derived from the light curve alone (Equation 6.31) provides a direct constraint on  $R_\star$ , and is a sensitive indicator of its evolutionary state. A more prescriptive form, dependent on the derived quantity ( $a/R_\star$ ), is

Table 6.1: Planetary and stellar parameters for WASP-52, illustrating the accuracy from transit observations. The orbit eccentricity is fixed as  $e = 0$ . From Hébrard et al. (2013b, Table 3).

Parameter	Value
Transit epoch, $T_0$ (HJD', d)	$5793.68143 \pm 0.00009$
Orbital period, $P$ (d)	$1.7497798 \pm 0.0000012$
Transit duration, $t_T$ (d)	$0.0754 \pm 0.0005$
Planet/star area ratio, $(R_p/R_\star)^2$	$0.0271 \pm 0.0004$
Impact parameter, $b$ ( $R_\star$ )	$0.60 \pm 0.02$
Scaled stellar radius, $R_\star/a$	$0.1355 \pm 0.0020$
Stellar density, $\rho_\star$ ( $\rho_\odot$ )	$1.76 \pm 0.08$
Stellar surface gravity, $\log g_\star$	$4.582 \pm 0.014$
Stellar radius, $R_\star$ ( $R_\odot$ )	$0.79 \pm 0.02$
Stellar mass, $M_\star$ ( $M_\odot$ )	$0.87 \pm 0.03$
Stellar rotation, $v \sin i_\star$ ( $\text{km s}^{-1}$ )	$2.5 \pm 1.0$
Star/planet axes projection, $\lambda$ ( $^\circ$ )	$24 \pm 13$
Semi-major axis, $a$ (au)	$0.0272 \pm 0.0003$
Orbital inclination, $i_p$ ( $^\circ$ )	$85.35 \pm 0.20$
Stellar reflex velocity, $K_1$ ( $\text{km s}^{-1}$ )	$0.0843 \pm 0.0030$
Planet radius, $R_p$ ( $R_J$ )	$1.27 \pm 0.03$
Planet mass, $M_p$ ( $M_J$ )	$0.46 \pm 0.02$
Planet surface gravity, $\log g_p$	$2.81 \pm 0.03$
Planet density, $\rho_p$ ( $\rho_J$ )	$0.22 \pm 0.02$
Planet temperature, $T_p$ (K)	$1315 \pm 35$

given by (Sozzetti et al., 2007)

$$\frac{M_\star}{R_\star^3} = \frac{4\pi^2}{GP^2} \left( \frac{a}{R_\star} \right)^3 - \frac{M_p}{R_\star^3}. \quad (6.43)$$

The first term on the right is entirely determined from measurable quantities while the second, although unknown until  $M_\star$  is determined, is two or more magnitudes smaller and can be ignored, at least for a first iteration (and included thereafter). As an example, for TrES-2, with  $P = 2.47063(1)$  d (O'Donovan et al., 2006a), and  $a/R_\star = 7.63 \pm 0.12$  (Holman et al., 2007b), the uncertainty on  $\rho_\star$  is only 1.6%.

A uniform re-analysis of transiting systems to establish  $\rho_\star$  has been made for 23 systems by Torres et al. (2008), and for 14 systems by Southworth (2008).

**Planet surface gravity** The planet's surface gravity,  $g_p$ , can be derived by combining the transit observations with parameters determined directly from the radial velocity reflex motion (Southworth et al., 2007). This follows from the mass function of a spectroscopic binary (cf. Equation 2.25)

$$\mathcal{M} = \frac{(1-e^2)^{3/2} K_\star^3 P}{2\pi G} = \frac{M_p^3 \sin^3 i}{(M_\star + M_p)^2}, \quad (6.44)$$

where  $K_\star$  is the radial velocity semi-amplitude. Including Kepler's third law (Equation 6.21) and solving for  $(M_\star + M_p)$  gives

$$g_p \equiv \frac{GM_p}{R_p^2} = \frac{2\pi}{P} \frac{(1-e^2)^{1/2} K_\star}{(R_p/a)^2 \sin i}. \quad (6.45)$$

$P$  can be obtained from the radial velocity, or the light curve, and is typically determined rather precisely. Radial velocities also give  $e$  and  $K_\star$ , while  $i$  and  $(R_p/a)$  are found from the transit light curve. An equivalent expression in terms of observables is (Torres et al., 2008, eqn 6)

$$\begin{aligned} \log g_p = & -4.1383 - \log P + \log K_\star \\ & - \frac{1}{2} \log \left( 1 - \left[ \frac{b}{a/R_\star} \frac{1-e^2}{1+e \sin \omega} \right]^2 \right) \\ & + 2 \log \left( \frac{a/R_\star}{R_p/R_\star} \right) + \frac{1}{2} \log(1-e^2), \end{aligned} \quad (6.46)$$

where the numerical constant is such that  $g_p$  is in  $\text{m s}^{-2}$  when  $P$  is in days and  $K_\star$  is in  $\text{m s}^{-1}$ .

Errors on the relevant light curve parameters show that it can provide a superior gravity indicator than the traditional estimate of  $\log g$  based on the widths of pressure-sensitive absorption lines. For HD 209458 b, for example, Southworth et al. (2007) determined  $g_p = 9.28 \pm 0.15 \text{ m s}^{-2}$ , an order of magnitude more precise than that obtained through measurement of its mass, radius and density. It confirmed that the planet has a lower surface gravity than that predicted by models of gas giant planets at the time.

In general, the immunity of  $g_p$  to systematic errors in stellar properties suggests that theoretical models of planet structure should be based on the comparison between theoretical and observed surface gravities, rather than theoretical and observed planet radii.

### 6.13.8 Doppler variability

A non-zero spectral index of the stellar spectrum means that there is a flux variability associated with any Doppler reflex motion. At non-relativistic velocities, and for circular orbits (Loeb & Gaudi, 2003, eqn 2)

$$\frac{\Delta F}{F} = (3-\alpha) \frac{K}{c}, \quad (6.47)$$

where  $K$  is the radial velocity semi-amplitude, and  $\alpha = d \ln(F_\nu) / d \ln \nu$  is the logarithmic slope of the source spectral flux in the observed frequency band, with  $\alpha \approx -1.3$  for solar-type stars observed in the optical band. For close-in planets with  $P \lesssim 0.2$  yr, the resulting periodic Doppler variability, of order  $\mu\text{mag}$ , is significant relative to variability caused by reflected light from the planetary companion, and dominates for  $P \gtrsim 0.2$  yr. The effect is relevant for almost any orbital inclination.

Loeb & Gaudi (2003) estimated that Kepler should have the photometric sensitivity to detect all planets with minimum mass  $M_p \sin i \gtrsim 5M_J$  and  $P \lesssim 0.1$  yr around the  $10^4$  main sequence stars with spectral types A-K and  $V < 12$  in its field of view. The extension to higher, stellar-mass binary companions was considered by Zucker et al. (2007).

Relativistic effects, in the form of Doppler beaming, are considered further in Section 6.15.4.

### 6.13.9 Secondary eclipse

The total light just before the time of the secondary eclipse is the sum of the stellar flux and that of the star. During the secondary eclipse the total light is that of the star alone. The difference therefore corresponds to the flux of the planet's day-side region. By measuring the relative depths of the secondary eclipse in multiple bandpasses, a low-resolution spectrum of the planet's flux can therefore be reconstructed.

Infrared photometry of the secondary eclipse also provides an estimate of the planetary temperature. In the Rayleigh–Jeans limit the depth of the secondary eclipse is given by (Charbonneau, 2003)

$$\Delta F \simeq \frac{T_p}{T_\star} \left( \frac{R_p}{R_\star} \right)^2. \quad (6.48)$$

For  $R_p = 1R_J$ ,  $R_\star = 1R_\odot$ , and planet/star temperatures of 1500 K and 6000 K,  $\Delta F \simeq 4$  mmag.

At optical wavelengths, the planet/star flux ratio is at least two orders of magnitude smaller than in the infrared, due to the planet's lower thermal emission at shorter wavelengths, and the low optical reflectance expected from cloud-free models (Figure 6.97). While detection of the secondary eclipse is therefore more difficult at optical wavelengths, it also provides important and complementary atmospheric diagnostics.

Details of transit and eclipse spectroscopy are given in §6.24, with associated atmospheric results in §11.6.

**Orbital dependence** The probability of an observable secondary eclipse depends on the orbital parameters of the planet, and particularly on its eccentricity and argument of pericentre. Kane & von Braun (2009) provide analytical expressions for the probabilities, calculate their values for the known transiting systems, and discuss constraints on the existence and observability of primary transits if a secondary eclipse is observed.

The timing of the secondary eclipse with respect to the primary transit is also related to the orbital eccentricity, and specifically to  $e \cos \omega$ . For example, the  $\simeq 1$  h secondary eclipse of GJ 436 b, with  $e = 0.15$ , occurs at orbit phase 0.587, more than five hours after the mid-point between transits (Deming et al., 2007a).

### 6.13.10 Planet mass determination

Mass constraints for planets are mainly based on radial velocity measurements. These are not well suited for planets with low masses, large semi-major axes, or those orbiting faint or active stars. For radial velocity measurements, prospects for determining the orbit inclination to resolve the  $\sin i$  ambiguity are noted in Section 2.5.5.

For transiting planets, mass estimates are possible through their effects on orbital phase curves. This approach is applicable to massive planets on short period

orbits, and involves detection of both beaming and ellipsoidal modulations (§6.15.5).

Mass estimates are also possible through transit-timing variations (§6.20). This approach is most successful for companions that are themselves transiting, and in orbital resonance with the planet of interest (Agol et al., 2005; Holman & Murray, 2005). For unseen companions the transiting planet mass is not constrained, but an upper limit on the mass of the unseen companion can be obtained to 15–50% (Steffen et al., 2013).

There are also prospects for determining the mass of transiting exoplanets based solely on transit observations, through its influence on the atmospheric scale height (box, page 208).

### 6.13.11 Asterodensity profiling

For a transiting system, whether planetary or eclipsing binary, *asterodensity profiling*, a term introduced by Kipping et al. (2012b), exploits the fact that the host's mean density,  $\rho_\star$ , can be determined by recourse to Kepler's third law on the basis of photometric transit data alone. If an independent stellar density is available, this has the potential to constrain various properties of the system, such as the planet's mass or eccentricity.

Based only on the four transit observables (the transit depth, mid-transit time, and durations of the first-to-fourth and second-to-third contacts,  $T_{14}$  and  $T_{23}$ ), under the assumption of a spherical, opaque, dark planet on a circular Keplerian orbit transiting a spherical, unblended host star, and invoking Kepler's third law, the stellar density can be written (Seager & Mallén-Ornelas 2003, Kipping 2014 eqn 4; see also §6.13.7)

$$\rho_{\star, \text{obs}} \equiv \frac{3\pi (a/R_\star)^3_{\text{obs}}}{GP^2}, \quad (6.51)$$

Limb darkening does not feature in the calculation of  $\rho_{\star, \text{obs}}$ , since it does not affect the transit durations.

This stellar density, derived from the transit light curve, can then be compared with independent measures,  $\rho_{\star, \text{true}}$ . If assumptions made in the definition of  $\rho_{\star, \text{obs}}$  are correct, then  $(\rho_{\star, \text{obs}}/\rho_{\star, \text{true}}) = 1$ . Deviation from unity provides insight into its physical origin. These assumptions include an opaque and spherical planet, a spherical star, non-variable transits, Keplerian circular orbit, and negligible blending from unresolved luminous objects.

For systems with multiple transiting planets, several measures of  $\rho_{\star, \text{obs}}$  are available, such that relative discrepancies in  $\rho_{\star, \text{obs}}$  can be examined, while making no assumption about the true stellar density. Such *multi-body asterodensity profiling* can provide constraints on mutual orbital eccentricities (Kipping et al., 2012b).

*Single-body asterodensity profiling* requires a reasonable constraint on  $\rho_{\star, \text{true}}$  (Kipping et al., 2012b).

**Planet mass from atmospheric scale height:** A method for determining the mass of transiting exoplanets based solely on transit observations, through its influence on the atmospheric scale height, and referred to as *MassSpec*, was proposed by de Wit & Seager (2013). It is based on the fact that the planet mass affects its transmission spectrum through the atmosphere pressure profile, i.e.  $p(z)$  where  $z$  is the altitude, and hence its atmospheric absorption profile. For an ideal gas atmosphere in hydrostatic equilibrium

$$\frac{d \ln p}{dz} = -\frac{1}{H}, \quad (6.49)$$

where  $H$  is the atmospheric scale height (Equation 6.153). Expressing the local gravity in terms of the planet's mass and radius, this can be rewritten

$$M_p = \frac{kTR_p^2}{\mu GH}. \quad (6.50)$$

The method requires constraining the radius of the planet as well as its atmospheric temperature, mean molecular mass, and scale height. With available instruments, the method is currently applicable only to hot Jupiters. Their mean molecular mass is known *a priori* (viz. for a H/He-dominated atmosphere,  $\mu \sim 2.3$ ), their temperature can be inferred from emission spectroscopy, and the measurement of the Rayleigh-scattering slope in transmission is directly related directly to its atmospheric scale height.

Based on estimates of  $T \approx 1300$  K,  $dR_p/d \ln \lambda \approx -920$  km, and  $R_p \approx 1.21R_J$  derived from emission and transmission spectra at  $0.8 \mu\text{m}$  (Pont et al., 2008a; Madhusudhan & Seager, 2009), the resulting estimate of the mass of HD 189733 b is  $1.15M_J$ , in agreement with that derived from radial velocity measurements,  $1.14 \pm 0.056M_J$  (Wright et al., 2011b). The method could be particularly important for gas giants whose host star's activity prevents a radial velocity mass measurement, e.g. WASP-33 b.

Accessible planets will extend to lower masses with high S/N spectra from JWST. For M9V stars with JWST, it could yield masses of mini-Neptunes, super-Earths, and Earth-sized planets up to distances of 500 pc, 100 pc, and 50 pc, respectively (de Wit & Seager, 2013). Challenges and degeneracies of the method for lower planet masses is considered by Batalha et al. (2017a).

A simple metric for estimating a planet's minimum atmospheric height, based only its radius and mass, exploits the boundary condition that the bulk composition of a solid/liquid super-Earth cannot be composed of a material lighter than water, such that mass-radius loci above a pure- $\text{H}_2\text{O}$  composition planet correspond to a minimum atmospheric height  $> 0$  (Kipping et al., 2013c).

Crucially,  $\rho_{\star, \text{true}}$  is a direct observable from asteroseismology, using the frequency spacing of pulsations modes (Ulrich, 1986).

Variants of asterodensity profiling have been applied to exoplanet studies, although not necessarily referred to as such. Thus  $\rho_{\star}$  can be used as a luminosity indicator for stellar evolution models, to obtain physical dimensions for the host star (Sozzetti et al., 2007).

Kipping (2014) has provided a set of analytic expressions for various effects which can cause a significant as-

terodensity profiling discrepancy, and hence can also be used as physical diagnostics. He denoted them collectively as photo-... effects, as summarised hereafter.

**Photo-mass effect** If the planet mass is not negligible in terms of the host mass (Kipping, 2014, eqn 7)

$$\left( \frac{\rho_{\star, \text{obs}}}{\rho_{\star, \text{true}}} \right)^{\text{PM}} = 1 + \frac{M_p}{M_{\star}}. \quad (6.52)$$

Ignoring the planet mass therefore leads to an overestimate of  $(\rho_{\star, \text{obs}}/\rho_{\star, \text{true}})$ . For an exoplanet, this *photo-mass effect* will be  $\lesssim 1\%$ , while for eclipsing binaries masquerading as planets through blending, it may be of order unity.

**Photo-blend effect** A key assumptions in the derivation of  $\rho_{\star, \text{obs}}$  is that the observed brightness variations are due to the host star alone, i.e. that the star is unblended. Blend sources come in many varieties involving triple and binary stellar configurations (e.g. Torres et al., 2011) as well as self-blending due to a hot compact object such as a white-dwarf or even a hot-Jupiter (Kipping & Tinetti, 2010). Blends are the bottleneck in validating the thousands of planetary candidates found by Kepler (e.g. Morton & Johnson, 2011b).

Defining the blend factor,  $\mathcal{B}$ , as the ratio of the total flux to that of the target's flux

$$\mathcal{B} \equiv \frac{F_{\star} + F_{\text{blend}}}{F_{\star}}, \quad (6.53)$$

the *photo-blend effect* is (Kipping, 2014, eqn 9)

$$\left( \frac{\rho_{\star, \text{obs}}}{\rho_{\star, \text{true}}} \right)^{\text{PB}} = \mathcal{B}^{-3/4} \left( \frac{(1 + \sqrt{\mathcal{B}} p_{\text{obs}})^2 - b_{\text{obs}}^2}{(1 + p_{\text{obs}})^2 - b_{\text{obs}}^2} \right)^{3/2}, \quad (6.54)$$

which can result in asterodensity profiling effects up to order unity. The assumption made to derive Equation 6.54,  $(a/R_{\star})^2 \gg (1 + p)^2$ , may also be expressed as

$$\left( \frac{P}{d} \right)^{4/3} \gg 0.389 \left( \frac{\rho_{\star, \text{true}}}{\text{kg m}^{-3}} \right)^{-2/3}. \quad (6.55)$$

Consequently, an independent measure of the stellar density can be used to measure the blend factor  $\mathcal{B}$ .

**Photo-spot effect** Star spots, networks and plages form in stellar magnetic fields generated by cyclonic turbulence in the outer convection zone of cool stars (Berdyugina, 2005). Star spots are thought to be a common outcome of this process, and continuous photometric monitoring reveals their signature as rotational modulations (§6.14.2). This has led to the determination of rotation periods for thousands of Kepler stars (§8.3).

While large spots which are occulted by the transiting object are relatively easy to identify and remove, unocculted spots are more challenging and perturb the

transit depth (Czesla et al., 2009). Kipping (2014) defines the effect of unocculted star spots perturbing the observed transit depth, and thus the observed stellar density, as the *photo-spot effect*.

Since  $\mathcal{B} \geq 1$  for all blend sources, the effect of a blend is to underestimate the stellar density. However, the change in transit depth due to unocculted star spots behaves like a  $\mathcal{B} < 1$  blend, enhancing the transit depth, and leading to  $(\rho_{\star, \text{obs}}/\rho_{\star, \text{true}}) > 1$ . Kipping (2012a) showed that the effect is given by

$$\frac{\delta_{\text{obs}}}{\delta_{\text{true}}} = \frac{F_{\star}(\text{unspotted})}{F_{\star}(\text{spotted})} = \frac{1}{1 - A_{\text{spots}}}. \quad (6.56)$$

where  $A_{\text{spots}}$  is the effective normalised photometric amplitude of the rotational modulations. The consequence on the stellar density is, analogous to the photo-blend effect (Kipping, 2014, eqn 21)

$$\left(\frac{\rho_{\star, \text{obs}}}{\rho_{\star, \text{true}}}\right)^{\text{PS}} = \lim_{\mathcal{B} \rightarrow \mathcal{B}_{\text{spot}}} \left(\frac{\rho_{\star, \text{obs}}}{\rho_{\star, \text{true}}}\right)^{\text{PB}} \quad (6.57)$$

**Photo-timing effect** Transit timing variations (TTVs) are common, with  $\sim 10\%$  of Kepler systems showing significant TTVs (§6.20). Low-amplitude variations can be difficult to detect by fitting individual transits and yet, if ignored, will systematically bias the transit parameters.

An object with low-amplitude TTVs ( $A_{\text{TTV}} < T_{23}$ ) with  $N \gg 1$  cycles will smear out a folded transit light curve. The four contact points appear shifted due to the planet motion, leading to erroneous  $T_{23}$  and  $T_{14}$  durations. This will affect the impact parameter, scaled semi-major axis, and light curve-derived stellar density.

The *photo-timing effect* is given by (Kipping, 2014, eqn 23)

$$\left(\frac{\rho_{\star, \text{obs}}}{\rho_{\star, \text{true}}}\right)^{\text{PT}} \geq \left(\frac{R_{\text{p}}/R_{\star}}{R_{\text{p}}/R_{\star} + nA_{\text{TTV}}(a/R_{\star})}\right)^{\frac{3}{2}}, \quad (6.58)$$

where  $n = 2\pi/P$ ,  $2A_{\text{TTV}}$  is the peak-to-peak TTV amplitude, and the approximation is valid for  $(a/R_{\star})^2 \gg 2$  and  $2A_{\text{TTV}} \ll T_{23}$ . The former may be expressed as

$$\left(\frac{P}{d}\right)^{\frac{4}{3}} \gg 0.231 \left(\frac{\rho_{\star, \text{true}}}{\text{kg m}^{-3}}\right)^{-\frac{2}{3}}. \quad (6.59)$$

A planet with  $P = 10$  d,  $R_{\text{p}}/R_{\star} = 0.1$  around a solar-like star, with each transit timed to a precision of 1 min over 4 yr of continuous monitoring, gives a maximum standard error  $\sigma(\rho_{\star, \text{obs}}/\rho_{\star, \text{true}}) \lesssim 9\%$ .

**Photo-duration effect** Transit durations variations (TDVs) are a related dynamical effect which will modify the shape of a folded transit light curve if unaccounted for (§6.20.10). TDVs were first posited as a signature of exomoons (Kipping, 2009a,b), but are also possible in strongly interacting multi-planet systems (Nesvorný

et al., 2012). TDVs come in (at least) two types, the dominant velocity-induced transit duration variations considered here, and transit impact parameter-dependent transit duration variations (§6.22.1).

TDVs essentially stretch and squeeze the width of the transit shape and a well-sampled periodic set of light curves with TDVs will exhibit a deformed folded transit shape if neglected. The *photo-duration effect* of periodic TDVs on the light curve derived stellar density is (Kipping, 2014, eqn 23)

$$\left(\frac{\rho_{\star, \text{obs}}}{\rho_{\star, \text{true}}}\right)^{\text{PD}} = \left(\frac{(\frac{a}{R_{\star}})^2 p + 4A_{\text{TDV}}^2 b^2 p + 2A_{\text{TDV}}[(1-p^2)^2 - b^2(1+p^2)]}{(\frac{a}{R_{\star}})^2 [p + 4A_{\text{TDV}}^2 p + 2A_{\text{TDV}}(1+p^2 - b^2)]}\right)^{\frac{3}{2}} \quad (6.60)$$

where  $p = R_{\text{p}}/R_{\star}$ , and where the expression is valid for  $(a/R_{\star})^2 \gg 2$  and  $A_{\text{TDV}} \ll 1$ .

For a planet with  $P = 10$  d,  $R_{\text{p}}/R_{\star} = 0.1$  around a solar-like star with  $b = 0$  ( $T_{14} = 4.3$  h), timing each transit to 1 min precision (corresponding to a 2 min duration uncertainty), over 4 yr of continuous monitoring, gives a maximum standard error  $\sigma(\rho_{\star, \text{obs}}/\rho_{\star, \text{true}}) = 10.6\%$ .

**Photo-eccentric effect** The effect of eccentricity is the most well-studied astero-density profiling effect. Dawson & Johnson (2012) already referred to it as the *photo-eccentric effect*, a convention followed by Kipping (2014). The effect is given by (Kipping et al., 2012b)

$$\left(\frac{\rho_{\star, \text{obs}}}{\rho_{\star, \text{true}}}\right)^{\text{PE}} = \frac{(1 + e \sin \omega)^3}{(1 - e^2)^{3/2}}, \quad (6.61)$$

and valid for (Kipping, 2014, equations 35–36)

$$\left(\frac{a}{R_{\star}}\right)^2 \gg \frac{2}{3} \left(\frac{1+e}{1-e}\right)^3, \quad (6.62)$$

which may also be expressed in physical units as

$$\left(\frac{P}{d}\right)^{\frac{4}{3}} \gg 0.101 \left(\frac{\rho_{\star, \text{true}}}{\text{kg m}^{-3}}\right)^{-\frac{2}{3}} \left(\frac{1+e}{1-e}\right)^3. \quad (6.63)$$

As variously noted (e.g. Burke, 2008; Kipping, 2008; Winn, 2010; Dawson & Johnson, 2012), if a planet on an eccentric orbit is observed to transit, then *a priori* it is more probable that  $0 < \omega \leq \pi$  than  $\pi < \omega \leq 2\pi$ . This is because the geometric transit probability is given by

$$P(b \leq 1) = \frac{1}{(a/R_{\star})} \frac{1 + e \sin \omega}{1 - e^2}, \quad (6.64)$$

such that

$$\frac{P(0 < \omega \leq \pi | b \leq 1)}{P(\pi < \omega \leq 2\pi | b \leq 1)} = \frac{\pi + 2e}{\pi - 2e}, \quad (6.65)$$

which is  $> 1$  for  $0 < e \leq 1$ . Although the ratio cannot be determined without assuming a prior eccentricity distribution, the consequence is that eccentric orbits lead to a (modest) overestimate of  $(\rho_{\star, \text{obs}}/\rho_{\star, \text{true}})$ .

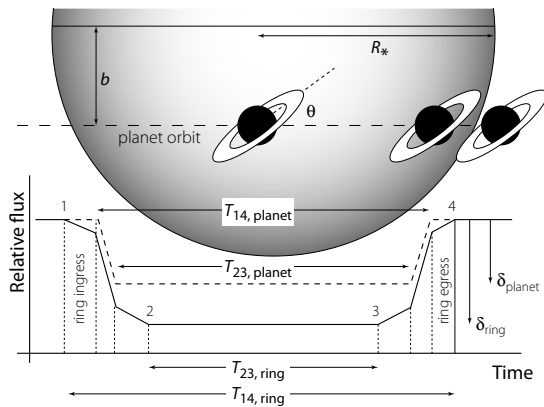


Figure 6.32: Schematic ring and planetary transit geometry and light curve (not to scale). The transit depth ( $\delta$ ) and total duration ( $T_{14}$ ) are larger when an exoring is present, while the duration of full transit ( $T_{23}$ ) is lower. From Zuluaga et al. (2015, Figure 1), by permission of IOP Publishing/AAS.

In applying this to constraints on orbital eccentricity, Dawson & Johnson (2012) proposed that even a loose prior on  $\rho_{\star,\text{true}}$  would be sufficient to identify highly eccentric planets. Referring to this as the ‘photo-eccentric effect’, Dawson & Johnson (2012) obtained  $e = 0.71^{+0.16}_{-0.09}$  for HD 17156 b, in good agreement with the radial velocity determination ( $e = 0.67 \pm 0.08$ ). Dawson et al. (2012) showed that Kepler-419 b (KOI-1474.01) has an eccentricity of  $e = 0.81^{+0.10}_{-0.07}$ .

The approach has also been used to constrain eccentricities for various individual systems, e.g. by examining anomalous transit durations (e.g. Dawson & Johnson, 2012; Dawson et al., 2012; Kane et al., 2012a; Kipping et al., 2013a), the asymmetry between ingress and egress shapes (Burke et al., 2007; Kipping, 2008), and the existence, timing, and duration of secondary eclipses (Kane & von Braun, 2009; Dong et al., 2013b). Limits of applicability are considered by Price et al. (2015).

This has been applied to assess habitability, where eccentric orbits can have profound effects (Dressing et al., 2010). It has also been applied to the eccentricities of entire populations (e.g. Moorhead et al., 2011; Kane et al., 2012a; Dawson et al., 2015b), e.g. as a constraint on planet-formation models (Ford & Rasio, 2008; Jurić & Tremaine, 2008; Socrates et al., 2012; Dong et al., 2013b).

Conversely, for planets with strong prior constraints on  $e$ , stellar densities and limb-darkening coefficients can be determined directly from the light curve. Sandford & Kipping (2017) fit a transit model, including a non-linear limb-darkening law, to 66 Kepler transiting planet hosts yielding, amongst others, densities to within 5% for the majority, with the dominant precision-limiting factor being the transit signal-to-noise ratio.

**Photo-ring effect** An analogous effect in the presence of planetary rings, the *photo-ring effect*, was described

by Zuluaga et al. (2015). Again, the principle is that a transiting ring system (Figure 6.32) could be revealed by a comparison of  $\rho_{\star}$  derived from the light curve to that measured independently, such as via asteroseismology. The maximum effect, over various projected ring inclinations, is given by (Zuluaga et al., 2015, eqn 13)

$$\left(\frac{\rho_{\star,\text{obs}}}{\rho_{\star,\text{true}}}\right)_{\text{max}}^{\text{PR}} \approx f_e^{-3/2} (1 - b^2)^{-3/4}, \quad (6.66)$$

where  $f_e = R_e/R_p$  is the external disk radius and  $b$  is the impact parameter. For their reference case,  $f_e = 2.35$ ,  $b = 0$ , the maximum value of the photo-ring effect,  $\log_{10}(\rho_{\text{obs}}/\rho_{\text{true}}) \sim -0.6$ , corresponds to an underestimation of  $\rho_{\star}$  by a significant factor of  $\sim 4$ . They stress that the method does not require a complex fit of transit light curves, instead relying on simple, analytic, and computationally efficient numerical procedures.

**Application to candidate validation** Sliski & Kipping (2014) selected 41 KOIs, with a single transiting candidate, for which the target star’s mean stellar density has been measured using asteroseismology. The ensemble of the asterodensity profile distribution for the 31 dwarf stars shows excellent agreement with the spread expected if the KOIs were genuine, with realistic eccentricities. The same test for the 10 giant stars, in contrast, reveals significant incompatibility, which they attribute to the transiting objects orbiting a different star to that measured with asteroseismology. Based on the asterodensity profile distribution, they estimate a false-positive rate for single transiting objects around giant stars of about  $70 \pm 30\%$ .

## 6.14 Higher-order photometric effects

In addition to the obscuration of the host star light by a uniform occulting disk, many other effects influence the details of transit photometry, resulting in a wide range of more complex light curves.

These include: the photometric non-uniformity of the stellar disk due to limb-darkening, the presence of star spots, and of gravity darkening; the presence of other associated bodies or material, such as moons, rings, and comets, as well as circumstellar and debris disks; other optical effects including refraction, micro-lensing amplification, Doppler beaming, reflection, and glint; and other complications such as grazing transits and planet–planet eclipses.

The rotationally- and tidally-distorted forms of a close-orbiting star–planet system also affect light curves in various ways, both as a consequence of the more complex geometric projections of their distorted figures, but also as a result of effects such as gravity darkening.

A combined discussion of the photometric, spectroscopic and dynamical effects is given for Trojans (§6.21), exomoons (§6.22), and exocomets (§6.23).

### 6.14.1 Limb darkening

Limb darkening refers to the drop of intensity in a stellar image moving from the centre to its limb, and results from the combined effects of optical depth with the decreasing star density and temperature with radius. It is typically represented by functions of  $\mu = \cos\theta$ , where  $\theta$  is the angle between the normal to the stellar surface and the line-of-sight to the observer. More completely, a transit light curve results from the attenuation of the stellar photosphere by the planet along with its own atmosphere, and therefore its own limb darkening.

The limb darkening functions of Claret (2000) provide suitable prescriptions and are widely used. In the non-linear law, the radial dependence of specific intensity is approximated by the fourth-order Taylor series

$$I(r) = 1 - \sum_{n=1}^4 c_n (1 - \mu^{n/2}), \quad (6.67)$$

with  $I(0) = 1$ , and coefficients  $c_i$  dependent on effective temperature, luminosity class, and metallicity. The quadratic law is a limiting case with  $c_1 = c_3 = 0$ .

The effect is very significant for planet transits, giving rise to a small colour change with wavelength already inferred by Rosenblatt (1971). It diminishes with increasing wavelength: in the mid-infrared, where many transit and secondary eclipse measurements are made, stellar disks are of rather uniform brightness, an approximation reasonably valid already in the near infrared.

Accurate transit modeling of HD 209458 by Deeg et al. (2001) was the first time that a limb-darkening sequence could be determined for a single late main sequence star beyond the Sun.

Other limb-darkening models and higher-order effects are noted in the box, page 211. Other manifestations of stellar centre-to-limb variations may be relevant in phenomena which rely on selective blocking of the stellar disk, including polarisation studies (§6.17.1), transit/eclipse spectroscopy (e.g. Yan et al., 2015b), and the Rossiter–McLaughlin effect (§6.18.3).

At photometric accuracies of 10–100 ppm expected for, e.g., JWST, the widely-adopted parametric laws introduce systematics that may mask such important higher-order effects, and direct centre-to-limb models must be used (Morello et al., 2017; Neilson et al., 2017).

**Algorithmic implementation** Algorithms for evaluating limb darkening include:

LDTK (Limb Darkening Toolkit) for calculating custom stellar limb darkening profiles and model-specific limb darkening coefficients using the PHOENIX spectral library (Parviainen & Aigrain, 2015).

limb-darkening and ld-exosim: codes to generate and optimise limb darkening coefficients for transit fits, using response functions based on ATLAS and PHOENIX model atmospheres (Espinoza & Jordán, 2015, 2016).

**Other limb-darkening models:** Claret & Bloemen (2011) gave revised calculations of limb-darkening coefficients for a wide range of stellar  $T_{\text{eff}}$ ,  $\log g$ ,  $[\text{Fe}/\text{H}]$ , and microturbulent velocities (for ATLAS and PHOENIX plane-parallel models), computed for the transmission curves of CoRoT, Kepler, and Spitzer, as well as the Strömgren, Johnson–Cousins, and Sloan systems, and with five equations used to describe the specific intensities (linear, quadratic, root-square, logarithmic, and a 4-coefficient law).

Other limb darkening models, covering (amongst others) the Kepler, WFCAM, and Hipparcos/Tycho passbands, are given by Howarth (2011a). Procedures for comparing limb-darkening coefficients from model atmospheres with those derived from photometry are described by Howarth (2011b). Coefficients from 3d hydrodynamical model atmospheres demonstrate improved fits to the HST data for both HD 209458 and HD 189733 (Hayek et al., 2012).

Csizmadia et al. (2013) evaluated the sensitivity of the derived ratio  $R_p/R_*$  on the assumed limb darkening, as a function of  $T_{\text{eff}}$ , concluding that the limb darkening coefficients should (generally) be left as free parameters.

Kipping (2013a) showed that unconstrained two-parameter fits are actually constrained, by three physical boundary conditions, to a triangular region in the 2d parameter space. Accordingly, a full search over this triangular region in the case of the widely-adopted quadratic law (for example) is most efficiently undertaken (and with robust and realistic uncertainty estimates) by fitting for  $q_1 = (u_1 + u_2)^2$  and  $q_2 = 0.5u_1(u_1 + u_2)^{-1}$ , with uniform priors on  $q_1$  and  $q_2$  in the interval  $[0, 1]$ .

As a result of these detailed models, for many applications limb darkening is nonetheless presumed to be known and modeled based on synthetic stellar atmospheres (e.g. Kjurkchieva et al., 2013a; Abubekerev et al., 2015). Müller et al. (2013b) measured limb darkening in 38 Kepler planetary candidate host stars ( $T_{\text{eff}} = 3000 - 8900$  K,  $\log g = 3.8 - 4.7$ ), with results consistent with the widely-used quadratic limb-darkening coefficients.

For models including tidal and rotational distortions, Claret & Bloemen (2011) computed gravity-darkening coefficients using the same grid of stellar atmospheres accounting for local gravity variations and convection. Results for spherically symmetric 1d PHOENIX models were given by Claret et al. (2012), for spherically symmetric ATLAS models by Neilson & Lester (2013), and for 3d STAGGER-code models by Magic et al. (2015).

ATLAS-based coefficients for the TESS mission, at several metallicities, surface gravities, and microturbulent velocities, are given by Claret (2017).

### 6.14.2 Star spots

In the context of transit light curves, star spots on the host star are common, are time-dependent both as a result of dynamo-driven evolution as well as stellar rotation, have a significant effect on the photometric measurements and, as a result, complicate the estimation of planetary parameters from transit photometry. They can lead to possible errors in planet size estimates if not accounted for (e.g. Czesla et al., 2009; Carter et al., 2011c; Walkowicz et al., 2013; Oshagh et al., 2016).

At the same time, star spots provide important diag-

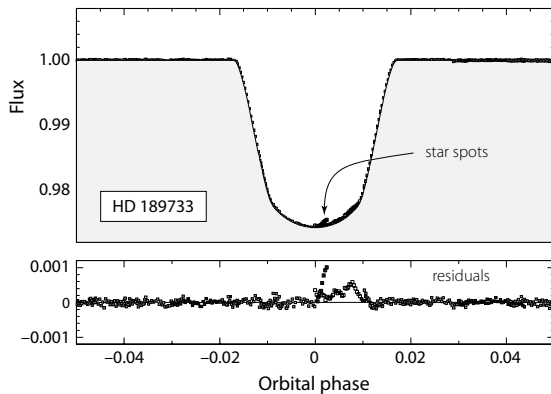


Figure 6.33: *HST-ACS* light curve for HD 189733 b, showing the effects of star spots on the detailed structure of the transit light curve (top), with residuals around the best-fit transit model (bottom). Residuals outside the spot complexes are at the  $\pm 10^{-4}$  level. From Pont et al. (2007a, Figure 1), reproduced with permission © ESO.

nostics of stellar rotation, including differential rotation and stellar obliquities.

Structure in high signal-to-noise transit curves was first attributed to flares or star spots in the case of HD 189733 b (Pont et al., 2007a, Figure 6.33), HD 209458 (Silva, 2008), TrES-1 (Dittmann et al., 2009b; Rabus et al., 2009a), and OGLE-TR-10 b (Bentley et al., 2009). Such spots are also frequently inferred from photometric (rotational) variability, e.g. as demonstrated for GJ 436 by Demory et al. (2007).

**Diagnostics of stellar activity** Photometric rotational modulation due to star spots provides an important diagnostic in studying underlying stellar activity. Kepler, in particular, with its precise continuous photometry of 150 000 stars, provides an unprecedented data set for statistical analyses of these modulations. Star spot occurrence as a function of host star type is detailed further in Section 8.3. Savanov (2015), for example, studied the dependence of spot coverage of stars with planets as a function of stellar  $T_{\text{eff}}$  and  $P_{\text{rot}}$ , finding no evidence that stellar magnetic activity depends on whether the star has planets; that the spot coverage of stars with planets mostly does not exceed 5%; for stars with  $T_{\text{eff}} < 5750$  K, there is a monotonic decrease of spot coverage with increasing  $P_{\text{rot}}$ ; and that stars with  $T_{\text{eff}} > 5750$  K have small spot coverage in the case of rapid rotation, increasing for stars with  $P_{\text{rot}} \sim 20 - 25$  d. Further constraints on spot properties versus spectral type come from the Kepler short-period binary stars (Balaji et al., 2015).

Modeling rotational modulations allows inversion of the observations into several basic parameters, such as the rotation period, spot coverage, stellar inclination and differential rotation rate (Nielsen & Karoff, 2012; Kipping, 2012a). The most widely used analytic model for this inversion comes from Budding (1977) and Dor-

ren (1987), who considered circular, grey star spots for a linearly limb darkened star. Kipping (2012a) extended the model to be more suitable in the analysis of high-precision photometry, such as that by Kepler.

**Algorithmic implementation** Various models for analysing transit light curves in the presence of star spots have been described. Amongst them:

**Cheetah** is an analytical model that uses the formulation of Eker (1994) to create a suite of synthetic light curves whose underlying parameters are known (Walkowicz et al., 2013). The main parameters are the linear and quadratic limb darkening coefficients, stellar inclination, spot locations and sizes, and the intensity ratio of the spots to the stellar photosphere.

**COMETS** uses analytical formulae to compare exoplanet and spot signals targeting observations using optical interferometry (Ligi et al., 2015).

**KSint** (Kelvin–Stokes integration) generates light curves with an arbitrary combination of spots and planets (Montalto et al., 2014, 2015a).

**Macula** allows for the effects of non-linear limb darkening, differential rotation, and star spot evolution, and also provides predictions of transit depth variations (Kipping, 2012b).

**PRISM** (Planetary Retrospective Integrated Star-spot Model) represents planetary transits with star spot crossings using a pixellation approach (Tregloan-Reed et al., 2013). It has been used to model star spot evolution in various systems, including WASP-19 (Tregloan-Reed et al., 2013; Mancini et al., 2013a), HATS-2 (Mohler-Fischer et al., 2013), Qatar-2 (Mancini et al., 2014c), and HAT-P-32 (Tregloan-Reed et al., 2018).

**SOAP** (Spot Oscillation And Planet Boisse et al., 2012a), and its upgrades SOAP-T (Oshagh et al., 2013a) and SOAP2 (Dumusque et al., 2014a), generate synthetic radial velocities and light curves for rotating spotted system as functions of the stellar rotation phase. The approach has been applied, for example, to HAT-P-11 (Oshagh et al., 2013a) and HD 189733 (Dumusque et al., 2014a).

**SPOTR0D** is a semi-analytic model for transits of spotted stars (Béky, 2014; Béky et al., 2014b).

**PyTransSpot** accounts for a transiting planet, limb darkening, and star spots (Juvan et al., 2018).

When comparing models with observations, the ‘unspotted’ luminosity of the star is unknown, such that models of inferred spot coverage will miss any non-varying component that might exist (e.g., symmetric polar spots). This uncertainty affects all star spot modeling efforts, and is a major error source in fitting for the true spot parameters (Kovari & Bartus, 1997).

**Effects on transit and star parameters** Simulations by Oshagh et al. (2013d) show that, if unaccounted for, a dark spot with the size of the largest sun spot can lead to underestimates of 4% in  $R_p$ , errors of  $\pm 4\%$  in transit duration, and transit timing variations of  $\sim 200$  s.

Carter et al. (2011c) gave a spotted star light curve model, and drew attention to the degeneracy between  $e$  and radius ratio (Figure 6.34). A more detailed consideration of modeling results and degeneracies is described by Walkowicz et al. (2013). They demonstrated that in the absence of additional constraints on the stellar inclination, such as spectroscopic measurements of  $v \sin i_*$  or occultations of star spots by planetary transits, the



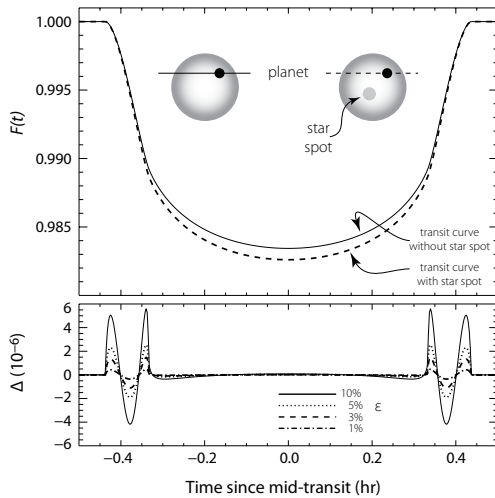


Figure 6.34: The effect of a non-transiting star spot, introducing a fractional loss of light  $\epsilon$ . Top: light curve of a transiting planet with (dashed line) and without (solid line) a star spot on the visible disk ( $\epsilon = 5\%$ ). Bottom: residuals between the two best-fit models for various value of  $\epsilon$ . From Carter et al. (2011c, Figure 3), by permission of IOP Publishing/AAS.

spot latitude and stellar inclination are difficult to determine uniquely from the photometry alone. For models with no differential rotation, spots that appear on opposite hemispheres of the star may cause one to interpret the rotation period to be half of the true period.

When differential rotation is included, the changing longitude separation between spots breaks the symmetry of the hemispheres, and the correct rotation period is more likely to be found. The dominant period found via periodogram analysis is typically that of the largest spot. Star spot modeling is applicable to stars with a wide range of rotation rates, and allows subtle signatures of differential rotation to be measured.

Due to limb darkening, the effects of star spots are much stronger near the centre of the star than at its limb (e.g. Sanchis-Ojeda et al., 2011). In contrast, star spot deviations have the greatest effect on a photometric model when they occur at the partial phases of the transit.

The existence of polar star spots will further complicate the interpretation of grazing transits, and may explain the paucity in their observed numbers (§6.14.14).

**Stellar rotation** If successive transits pass across the same star spots, the stellar rotation period may be determined independently from rotationally-broadened spectral lines (Silva, 2003). For a suitably-aligned star, the spot structure will recur in successive transits for as long as the spot is on the visible hemisphere, steadily advancing in phase due to the star's rotation between transits. Silva (2008) used structure in the four HST transits of HD 209458 b by Brown et al. (2001) to derive a stellar rotation period of 9.9 or 11.4 d. Stellar rotation commen-

**Active latitudes in solar astronomy:** Solar astronomy embraces the phenomenon of *active latitudes*. Sun spots are most abundant in two relatively narrow bands disposed symmetrically with respect to the solar equator. Over the Sun's 11-yr activity cycle their mean latitude, well defined over any interval of several months, undergoes a gradual shift from high latitudes to the equator (Carrington, 1858; Spörer, 1874). Early in the solar cycle, spots appear at latitudes up to  $40^\circ$ . As the cycle progresses, new sun spots appear at increasingly lower latitudes, with the last sun spots of a cycle lying close to the equator (Solanki, 2003). The *butterfly diagram* (Maunder, 1904), in which sun spot latitude is shown against time, illustrates this 'Spörer's law'.

surate with orbital period has been identified for various systems, including HAT-P-11 (Béky et al., 2014a), and the brown dwarf CoRoT-33 (Csizmadia et al., 2015).

**Effects on transit duration** Loeb (2009) quantified the effect on the transit duration caused by variations in photospheric radius of the host star due to changes in magnetic activity. Effects would be larger for M dwarfs. Studies for CoRoT-2 were made by Czesla et al. (2009).

**Examples** Transiting systems whose host stars exemplify detailed spot models include (lexically)  $\epsilon$  Eri (Croll et al., 2006), CoRoT-2 (Alonso et al., 2008a; Czesla et al., 2009; Silva-Valio et al., 2010), GJ 436 (Ballard et al., 2010b), GJ 674 (Bonfils et al., 2007), GJ 1214 (Carter et al., 2011c; Kundurthy et al., 2011; Berta et al., 2011), HAT-P-11 (Sanchis-Ojeda & Winn, 2011; Southworth, 2011; Sada et al., 2012), HATS-2 (Mohler-Fischer et al., 2013), HD 192263 (Dragomir et al., 2012a), Kepler-17 (Bonomo & Lanza, 2012), Kepler-30 (Fabrycky et al., 2012; Sanchis-Ojeda et al., 2013b), Kepler-32 (Fabrycky et al., 2012), Qatar-2 (Mancini et al., 2014c), WASP-4 (Sanchis-Ojeda et al., 2011), WASP-10 (Maciejewski et al., 2011c; Barros et al., 2013), WASP-11 (Sada et al., 2012), WASP-19 (Tregloan-Reed et al., 2013), and WASP-33 (Kovács et al., 2013b).

Southworth (2011) identified HAT-P-11 b, with the planet orbit almost orthogonal to the stellar rotation axis, as exceptional for star spot studies. Of the 25 transits observed by Kepler at that time, many are '*marvellous examples of a planet transiting a star spot or star spot complex, and all are affected to some degree*' (Figure 6.35). The ratio of the orbital to stellar spin periods is close to 6.0, so every sixth transit crosses over nearly the same part of the stellar surface and thus is similarly affected by spots which evolve on a time-scale of 29 d or less (Winn et al., 2010c). Its oblique orbit also means that it transits, at some point, a much greater fraction of the stellar surface than an aligned system, and with a wide distribution of latitudes.

**Distribution with stellar latitude** If spots occurred with equal probability at any latitude, the distribution of outliers would be quasi-uniform, except near ingress and egress where limb darkening and geometrical foreshortening would make some spots undetectable. Similarly, if the stellar obliquity  $\psi = 0$ , then a quasi-uniform distribution of residuals would be observed, even if the spots were clustered in latitude.

Results for HAT-P-11 exhibit two peaks (Figure 6.35). Sanchis-Ojeda & Winn (2011) concluded that the system is misaligned, and that star spots occur preferentially at

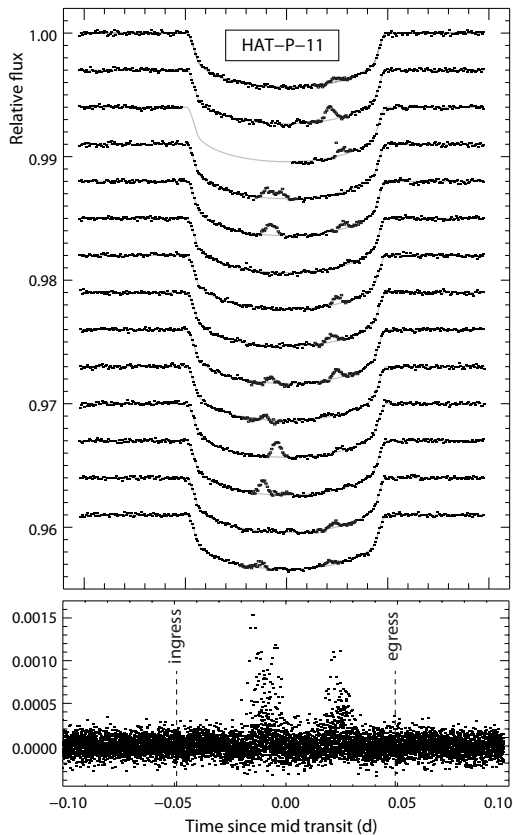


Figure 6.35: Top: Kepler transit observations of HAT-P-11. Thin grey lines are the best-fit models. Open squares are suspected of being affected by spot-crossings, and assigned zero weight. Bottom: residuals from the best-fit model based on 26 transits. Spot-crossing anomalies (large positive residuals) appear preferentially at two particular phases, asymmetric with respect to mid-transit. From Sanchis-Ojeda & Winn (2011, Figures 3 and 5), by permission of IOP Publishing/AAS.

certain active latitudes. Similar behaviour occurs in the Sun (box, page 213). The similarity in the spot sizes and distributions between HAT-P-11 and the Sun suggests a solar-like dynamo operating in HAT-P-11, although with a spot coverage of  $\sim 3\%$ , some two orders of magnitude greater in area (Morris et al., 2017b).

**Stellar obliquities: individual stars** Various techniques can probe the alignment between the axes of stellar rotation and planetary orbital motion (§8.3.2). For spotted stars, the behaviour of the spot structure across successive transits provides an important alignment constraint (Winn et al., 2010c), with extended high-accuracy photometric coverage by CoRoT and Kepler of particular value. Qualitatively, a low obliquity leads to the close recurrence of star spots from one transit to the next, while for progressively higher obliquities any given spot will rotate more rapidly away from the transit chord (Nutzman et al., 2011a; Llama et al., 2012).

More quantitatively, a spot model, parameterised by the spin orientation of the star, predicts when the planet will transit the spots. Observing multiple spot crossings during different transits then leads to constraints on the (spin-orbit related) angle  $\lambda$  (§6.18; see also Figure 6.69). In cases where the star spots are small, the stellar inclination,  $i_*$ , and hence the true alignment (rather than just the sky projection), can be inferred.

**Applications** Such a phenomenological interpretation and analysis was applied to WASP-4 b using Magellan photometry by Sanchis-Ojeda et al. (2011).

For CoRoT-2, Nutzman et al. (2011a) employed a more global solution, using the analytical star spot model for circular spots and linear limb darkening due to Dorren (1987), and the three-spot differential rotation model for CoRoT-2 derived by Fröhlich et al. (2009). Their model allows for differential rotation by fitting the period of each spot independently, then fitting five parameters for each spot (radius, latitude, and brightness ratio, and the period and epoch of rotation), along with a linear limb-darkening parameter and the stellar spin inclination  $i_*$  (Figure 6.36).

For Kepler-17 b, continuous monitoring by Désert et al. (2011b) revealed star spots frequently occulted by the planet, leading to a stellar rotation period of 11.89 d which, at eight times the planet's orbital period, produces stroboscopic effects on the occulted spots. Their temporal pattern shows that the planet's orbit is prograde, with stellar obliquity  $\psi < 15^\circ$ .

Similar methods have since been applied using Kepler data for various systems including HAT-P-11 (Sanchis-Ojeda & Winn, 2011), Kepler-30 (Sanchis-Ojeda et al., 2013b), and others (e.g. Hirano et al., 2012b), and using Kepler/K2 data for Qatar-2 (Dai et al., 2017b) and WASP-107 (Dai & Winn, 2017).

**Stellar obliquities: statistical** More generally, the observed amplitude of the rotational photometric modulation of a star with spots should depend on the inclination of its rotation axis relative to the line-of-sight. The distribution of observed rotational amplitudes of a large sample of stars will therefore depend on the distribution of their projected axes of rotation. Consequently, in the case of Kepler stars, a comparison of the stellar rotational amplitudes of (planetary candidate) Kepler 'Objects of Interest' (KOI, see box, page 175) with those of single stars can provide a constraint on the spin-orbit obliquities of Kepler planetary systems.

Mazeh et al. (2015b) applied this to 993 KOIs and 33 614 single Kepler stars in range  $T_{\text{eff}} = 3500 - 6500$  K. They found that the amplitudes of cool planet hosts are 10% larger than those of the single stars, while the amplitudes of the hot planet hosts are smaller than the single stars by about the same factor of 10%, with the break occurring at  $\sim 6000$  K. Their results suggest that cool stars have planets (generally) aligned with their stellar rotation, while the planets around hot stars have large obliquities, consistent with earlier findings on individual stars (cf. §6.18.7; Winn et al., 2010a; Albrecht et al., 2012b).

The low obliquity of planets around cool stars extends to  $\geq 50$  d, a feature unexpected if low obliquity is attributed to planet-star tidal realignment.

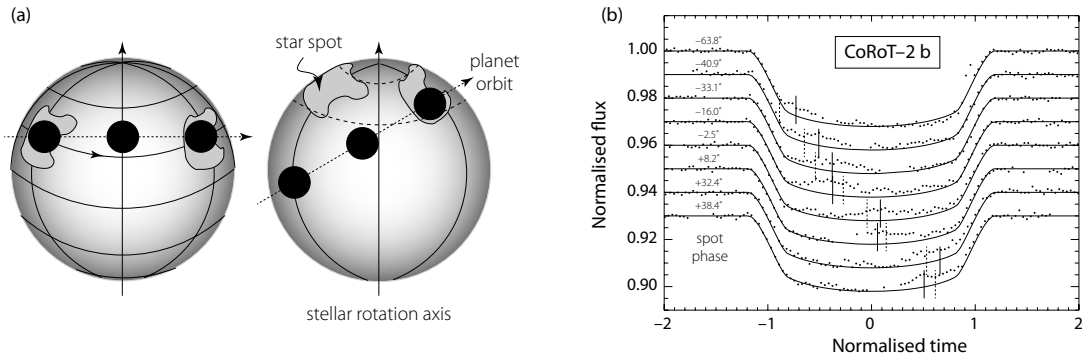


Figure 6.36: (a) Schematic of spot crossings for a well-aligned (left) and misaligned (right) planetary orbit, with spot shown before and after a  $120^\circ$  rotation of the star. The relative size and impact parameter of the planet reflect the properties of the CoRoT-2 system. (b) Transit light curves for CoRoT-2 b in order of increasing spot rotational phase. Generally, the spot is occulted at progressively later positions in the transit light curve, suggesting that the planet's orbit is prograde, relatively well aligned with the projected stellar spin axis, and that the bumps represent the same spot being occulted by the planet multiple times. Solid bars indicate the measured spot-crossing times, and dashed bars indicate the expected spot-crossing time for a well-aligned planet with  $\lambda = 0$ ,  $i_* = 90^\circ$ . From Nutzman et al. (2011a, Figures 2–3), by permission of IOP Publishing/AAS.

**Relevance for transit time variations** The presence of star spots can affect transit time determinations, and so must be considered in any models of transit time variations attributed to dynamically-interacting companions (§6.20). Simulations by Ioannidis et al. (2016) suggest that transit time shifts cannot exceed 1% of the transit duration, and that these depend strongly on the longitudinal position of the spot during the transit as well as on the transit duration. Consequently, transit time variations larger than this limit are unlikely to be caused by star spots, while low-amplitude transit time variations around active stars are the most problematic cases.

Transit timing variations originating from rotating stellar spots provide a diagnostic for distinguishing between prograde and retrograde orbital motion, as a result of the expected correlation between transit time variations and the stellar brightness derivative across a relevant transit (Mazeh et al., 2015a; Holczer et al., 2015).

Specifically, a spot crossing by the planet can induce a positive transit time shift if the crossing occurs in the first half of the transit, while the motion of the spot towards the centre of the stellar disk causes the stellar brightness to decrease (and *vice versa*). Accordingly, for a planet with prograde motion, the induced transit time variation is positive when the local slope of the stellar flux at the time of transit is negative, and *vice versa*. Quantitatively, a system with  $R_{\text{spot}} \approx R_p \approx 0.1R_*$ ,  $(1 - a)/4 \approx 0.25$  (where  $a$  characterises the surface brightness of the spot), and a transit duration of 3 h, should show an induced transit time variation of  $\sim 5$  min.

Holczer et al. (2015) examined a selected subset of 2600 KOIs, identifying nine systems where the photometric spot modulation is large enough and the transit timing accurate enough to allow detection of a correlation between the transit time variation and the bright-

ness derivatives. Of these, five show significant prograde motion (including Kepler-17, Kepler-71, and Kepler-762), while none display retrograde motion, consistent with the finding that most cool planet-host stars have close to zero obliquity (Winn et al., 2010a).

They also found evidence that star spots occur preferentially at low stellar latitudes, but not exactly along the stellar equator, viz. as seen with the Sun (box, page 213). The technique may have wider applicability to K2, TESS, and PLATO data.

### 6.14.3 Stellar rotation and gravity darkening

**Introduction** A star that rotates fast enough to become oblate also shows brightness variations across its disk, a phenomenon referred to as the *Von Zeipel effect* (von Zeipel, 1924). The rapid stellar rotation results in an equator-to-pole gradient in the effective surface gravity. The atmospheric scale height is larger near the equator, the photosphere consequently occurs at a lower pressure level than it does at the poles, with a correspondingly lower temperature. The stellar disk therefore shows hotter and brighter poles, with cooler and dimmer equatorial regions, referred to as *gravity darkening*.

The effect, first considered for eclipsing binary stars by Russell (1939), is now regularly used to characterise close binary star photometry (e.g. Djurasevic et al., 2003), where the asymmetry can also be used to constrain the spin-orbit alignment (e.g. Philippov & Rafikov, 2013). The theoretical framework is substantiated by optical interferometric observations of the rapidly rotating stellar disks of Vega (Peterson et al., 2006), Altair (Monnier et al., 2007), and an increasing number of other nearby stars (van Belle, 2012).

Compared to the slowly-rotating Sun, very nearly a perfect sphere (§12.1.7; see also box, page 216), there are

**Oblate and spherical stars:** The average radius of the Sun determined with SOHO is  $959.28 \pm 0.15$  arcsec (Kuhn et al., 2004). The variation of  $0.009 \pm 0.002$  arcsec from equator to pole implies an oblateness  $(b/a - 1) < 10^{-5}$  (Rozelot et al., 2003). A value  $8.34(\pm 0.15) \times 10^{-6}$  was determined from SDO-HMI (Kuhn et al., 2012).

Extremely rapid rotators include  $\alpha$  Leo A (Regulus), with  $v_{\text{rot}} \sin i = 317 \text{ km s}^{-1}$ ,  $P = 15.9 \text{ h}$  (86% of the break-up velocity), and  $R_{\text{eq}} = 1.32 R_{\text{pol}}$  (McAlister et al., 2005). Other rapidly rotating stars include Vega and Achernar.

At the other extreme, KIC-11145123, with  $P_{\text{rot}} \sim 100 \text{ d}$ , has been claimed as the ‘roundest’ object in Nature, with an asteroseismology-determined  $\Delta R/R = (1.8 \pm 0.6) \times 10^{-6}$  which, for  $R_{\star} = 2.3 R_{\odot} \sim 1.5 \text{ Mkm}$ , implies  $\Delta = 3 \pm 1 \text{ km}$  between its polar and equatorial radii (Gizon et al., 2016).

a number of stars with a measured oblateness in excess of 20%, leading to photospheric temperatures hotter at the pole than the equator by several thousand K.

**Constraints on spin-orbit alignment** Barnes (2009) demonstrated how rapid rotation of a transit host star would lead to distinctive light curves from which the relative alignment of the stellar rotation pole and the planet orbit normal can be derived. It is analogous to the Rossiter–McLaughlin effect on the radial velocities, and could similarly be used to constrain theories of planet formation and migration, especially for rapid rotators where radial velocity measures are difficult.

Stellar oblateness will alter the transit ingress and egress times, and the overall transit duration, somewhat complementary to the effects of planetary oblateness (Seager & Hui, 2002; Barnes & Fortney, 2003). When the stellar spin axis and the planet’s orbital axis are aligned, the Von Zeipel effect will cause systematic errors in radius determinations for the star and the planet, especially for high impact parameter, and will lead to broad-band colour variations during transit (Barnes, 2009).

For non-aligned geometries, the resulting asymmetric transit light curves can constrain both the stellar spin pole direction and the spin-orbit alignment. Compared with the Rossiter–McLaughlin effect, this technique has the capability of measuring both the longitude of the planet’s ascending node, and the stellar obliquity to the plane of the sky. At the same time, the resulting distorted light curves may not be immediately recognisable as planetary transits (Figure 6.37). Barnes (2009) estimates that some 5–10% of the Kepler target stars should be rapid rotators.

For rapidly-rotating stars with a large quadrupole moment, constraints are available in principle from variations in transit duration as a result of the precession of the line of nodes of the orbit plane. In the case of CoRoT-11, significant changes on a time scale of  $7 \times 10^4 \text{ yr}$  are predicted (Lanza et al., 2011c).

**Specific systems** These include:

*Kepler-13 b:* Szabó et al. (2011) reported an asymmetry in the

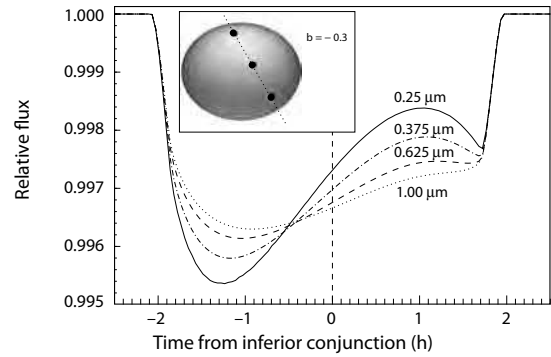


Figure 6.37: Model light curves for a  $1R_J$  planet in a  $0.05 \text{ au}$  orbit around an Altair-like star with a  $60^\circ$  obliquity (inset). Curves correspond to a transit impact parameter  $b = -0.3R_{\text{pole}}$  at different wavelengths, assuming identical limb darkening. The contrast is greatest at the short-wavelength (Wien) side of the blackbody curve, and least at the long-wavelength (Rayleigh–Jeans) side. From Barnes (2009, Figure 9), by permission of IOP Publishing/AAS.

transit light curve of Kepler-13 b that they attributed to spin-orbit misalignment around a fast-rotating star. Barnes et al. (2011b) used this asymmetry to measure the spin-orbit misalignment angle  $\psi$  of the system (Figure 6.38). They determined a sky-projected alignment of  $\lambda = 23 \pm 4^\circ$ , the star’s north pole tilted away from the observer by  $48 \pm 4^\circ$ , and a resulting net misalignment between the planet’s orbit normal and the star’s rotational pole of  $56 \pm 4^\circ$ . This represented the first spin-orbit measurement to come from gravity darkening, and still one of only a few measurements of the true (not just the sky-projected) spin-orbit misalignment (§8.3.2). Subsequently, Szabó et al. (2014) measured changes in transit duration and transit depth consistent with the expected precessing orbit (Figure 6.39).

*Kepler-1115 b:* a probable spin-orbit aligned super-Earth (Barnes et al., 2015a).

*CoRoT-29:* asymmetric transits, perhaps due to stellar oblateness, were reported by Cabrera et al. (2015, see Figure 6.40), although not confirmed by Pallé et al. (2016a).

*PTFO 8-8695:* this is discussed further in Section 6.19.5.

#### 6.14.4 Binary planets

Ochiai et al. (2014) investigated the formation of gravitationally bounded pairs of gas giants, which they termed *binary planets*, from capture through planet–planet dynamical tides during close encounters, and their subsequent long-term tidal evolution. After first entering a spin-orbit synchronous state, they eventually collide. Beyond  $\sim 0.3 \text{ au}$  from the central star, they could survive for the solar mass main-sequence lifetime,  $\sim 10 \text{ Gyr}$ . Ochiai et al. (2014) found a formation rate, amongst orbit crossing gas giants, of some 10%.

Using these constraints, Lewis et al. (2015) modeled transit light curves of plausible binary planets. They show prominent dips or bumps, are qualitatively different from those of a single planet (Figure 6.41), and with a profile changing from transit to transit. Because of this,

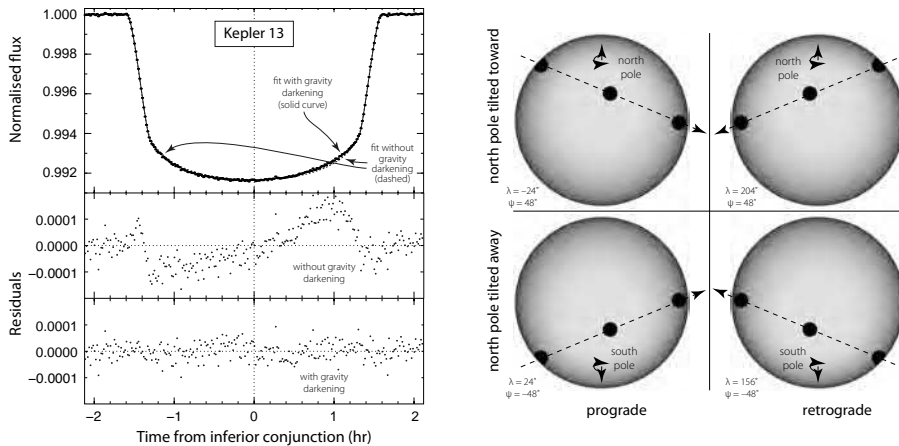


Figure 6.38: Left: transit light curve for Kepler-13 b, with best-fit lines with (solid curve) and without (dashed curve) gravity darkening, assuming  $M_{\star} = 2.05M_{\odot}$ . Residuals for both fits are shown below. Right: possible geometries for the Kepler-13 b transit, assuming  $M_{\star} = 2.05M_{\odot}$ . Due to the competing effects of limb darkening and gravity darkening, the stellar poles are not the brightest regions of the stellar disk. Gravity darkening displaces the brightest part of the disk from the centre towards the pole. From Barnes et al. (2011b, Figures 2 and 3), by permission of IOP Publishing/AAS.

Lewis et al. (2015) also suggested that binary planet transits might well be classified as false-positives. A single planet fit for two equal-sized binary planets could also give a lower bulk density than the true value, perhaps causing them to be classified as ‘inflated’ (§6.28.4). They proposed a binary planet explanation for the CoRoT candidate SRc01 E2 1066 (Erikson et al., 2012).

### 6.14.5 Exoplanetary rings

If a planet is surrounded by rings with significant opacity, the transit light curve would be distorted relative to a spherical body (Figure 6.32), with dips before first and after fourth contact (Schneider et al., 1998; Schneider, 1999; Arnold & Schneider, 2004; Barnes & Fortney, 2004; Johnson & Huggins, 2006; Heising et al., 2015; Aizawa et al., 2017; Hatchett et al., 2018), and with associated effects on the (Rossiter–McLaughlin) line profile distortions (de Mooij et al., 2017).

Zuluaga et al. (2015) also predicted large amplitudes, and considered that a significant perturbation in transit depth could lead rings to be mis-classified as false-positive. They also described a related asterodensity profiling effect, termed the *photo-ring effect*, revealed by a comparison of the stellar density derived from the light curve to that measured with independent methods such as asteroseismology (§6.13.11).

Hedman (2015) hypothesised that dense rings in the system, found only between 8–10 au, may indicate that rings arise from the weakness of icy material at  $\sim 70$  K, in which case exoring detections may require transits of long-period ( $\geq 10$  yr) giants planets outside their star’s ice lines. A number of such systems are expected from Gaia (Perryman et al., 2014a, see also §3.9.3).

Schlichting & Chang (2011) investigated the likely properties of rings around exoplanets inside the ice line, finding that most known planets with reliable sizes have sufficiently large Roche radii to support rings. They evaluated the effects of Poynting–Robertson drag on their lifetimes, and prospects for determining the planet’s J2 from warped structures.

**Searches and candidates** For HD 209458 b, Brown et al. (2001) placed limits on any ring radius of  $1.8R_{\text{p}}$ , slightly smaller than the radius of Saturn’s ring system when measured in units of Saturn’s radius. The low sensitivity is a consequence of the assumption that rings must lie in the planet’s orbital plane, and hence nearly edge-on as seen from Earth.

A search for planetary rings in 21 Kepler planets, mostly hot Jupiters, provided upper limits on Saturn-like rings, at least for certain orientations, for 12, while their models suggested that detection for favourably-oriented rings was feasible (Heising et al., 2015). From 89 long-period Kepler planets, KIC-10403228 was identified as a ring candidate from its transit profile by Aizawa et al. (2017, their Figure 9).

Possible rings have been suggested in the cases of 1SWASP J1407 (§6.14.6), KIC-8462852 (§6.14.22), RIK 210 (David et al., 2017), and PDS 110 (Osborn et al., 2017a). Sucerquia et al. (2017) suggested that these could be tilted exorings (Lidov–Kozai) disturbed by a third close companion, with attendant complex changes in shape and orientation.

**Algorithms** SOAP3.0 is a numerical tool to simulate ringed planet transits and measure ring detectability (Akisanmi et al., 2018). They suggest that ESPRESSO and CHEOPS will have the accuracies needed for detection.

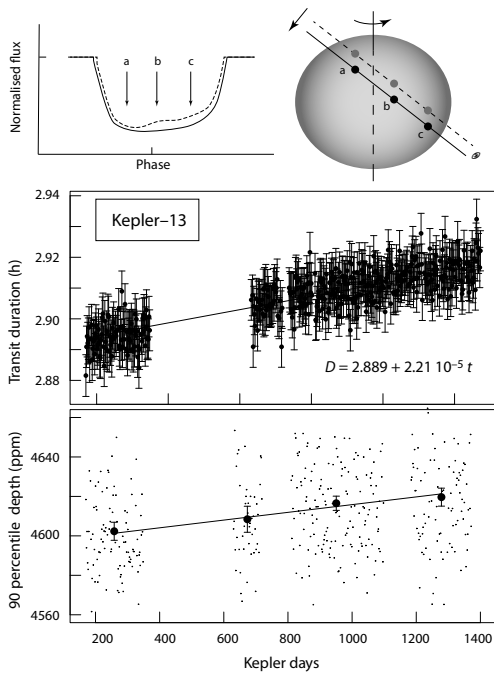


Figure 6.39: Top: schematic of a transiting planet on a precessing orbit, showing the expected differences in light variation (left) as a function of the part of the stellar disk occulted (originally from Szabó et al., 2011). Middle: observed variation of transit duration for Kepler-13. Bottom: variation of the transit depth, expressed in term of the 90 percentile. From Szabó et al. (2014, Figures 1 and 3), © Oxford University Press.

#### 6.14.6 Debris and transition disks

Debris disks, resulting from collisional attrition, are known to exist around many stars, including a number of planet hosting stars (§10.6). Resolved images of the outer regions of several (such as  $\beta$  Pic and AU Mic) reveal asymmetric structures in the form of rings, gaps, and clumps, likely created by gravitational perturbations and resonances from unseen planets. Their large relative sizes, and expected structural inhomogeneities, suggests that they might result in observable photometric variability in at least some transiting systems.

Similar structures have been widely identified in the younger transition disk systems, in which disk clearing and planet formation is ongoing (§10.3.8). Asymmetries in the inner regions of these various edge-on disks could produce photometric variations in transiting light curves in the form of deficits and clumps (e.g. Stark & Kuchner, 2008; Stark, 2011; Stark et al., 2015).

Within the solar system's (debris disk) zodiacal dust cloud (§12.5.13), which also defines the unit of exozodiacal dust, the 'zodi' (box, page 342), at least one such clumpy structure exists in its inner regions, the *zodiacal cloud*. Infrared COBE-DIRBE satellite observations confirmed excess flux leading and trailing the Earth's orbit

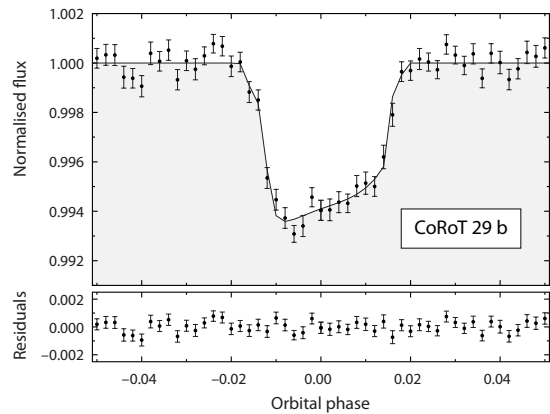


Figure 6.40: The binned and folded light curve of CoRoT-29 b, together with the best fit accounting for gravity darkening, suggestive of a rapidly spinning host star. From Cabrera et al. (2015, Figure 13), reproduced with permission © ESO.

(Reach et al., 1995), interpreted as a circumsolar ring of dust resonantly trapped by the Earth (Jackson & Zook, 1989; Dermott et al., 1994).

Models of the transit light curves of collisional exozodiacal clouds with these asymmetric structures (Stark, 2011) typically exhibit two broad transit minima that lead and trail the planetary transit. Jupiter-mass planets embedded within disks hundreds of times denser than the solar system zodiacal cloud can create resonant ring structures with transit depths up to  $10^{-4}$ , possibly detectable with current instrumentation (Figure 6.42).

**Searches** Krivov et al. (2011) searched for infrared excesses in such systems in the Wide-field Infrared Survey Explorer (WISE) catalogue, finding 52 stars with transiting planets, of which two systems with transiting hot Jupiters, TrES-2 and XO-5, exhibit small excesses both at 12 and at  $22 \mu\text{m}$ . The implied frequency of warm excesses in systems with transiting planets of 2–4% is comparable to that around solar-type stars probed at similar wavelengths with Spitzer-MIPS and IRS. Modeling suggests that the observed excesses would result from dust rings with radii of several au.

Ribas et al. (2012) found 13 Kepler host stars showing excesses at 12 or  $22 \mu\text{m}$ , suggestive of debris disks.

Mamajek et al. (2012) estimated that a survey of  $10^4$  young (10 Myr) post-accretion pre-main-sequence stars monitored for 10 years should yield at least a few deep eclipses from circumplanetary disks and disks surrounding low-mass companion stars.

**1SWASP J1407** Such a candidate was found in the SuperWASP monitoring of 1SWASP J1407 (strictly 1SWASP J140747.93–394542.6, cf. box, page 432; also V1400 Cen). The system displayed a long (54 d), deep (0.5–3.3 mag), and complex eclipse event observed by SuperWASP in 2007 (Mamajek et al., 2012). The host

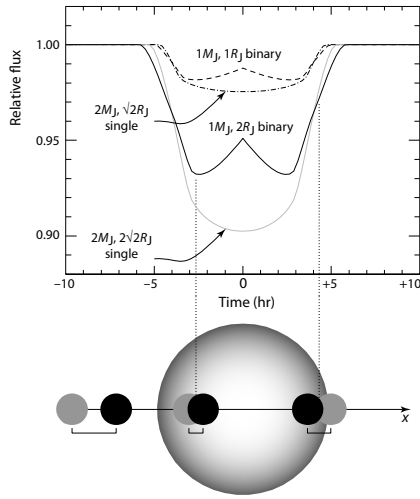


Figure 6.41: Simulated binary planets transiting a solar-like limb-darkened star. Top: transit light curves, for  $b = 0$ , as the binary planet undergoes a mutual event along the line-of-sight, for two binary configurations. The standard single-planet light curves for the same total mass are also shown. Bottom: schematic showing the transiting binary planet in front of the stellar photosphere. From Lewis et al. (2015, Figure 2), by permission of IOP Publishing/AAS.

star is a young  $0.9M_{\odot}$  member of the 16 Myr old Upper Centaurus–Lupus subgroup of Sco–Cen at  $d \sim 128$  pc. It has been modeled as a system of circumstellar or circumplanetary disks at  $r > 1.7$  au, comprising a dense inner disk accompanied by at least three dusty rings of optical depth near unity. Between these rings are at least two gaps of near-zero optical depth, possibly cleared out by planets or moons (Figure 6.43). For possible periods in the range 2.33–200 yr, the ring mass is  $\sim 0.4–8M_{\text{Moon}}$ . Further observations and characterisation of the ring systems have been made (van Werkhoven et al., 2014b; Kenworthy et al., 2015; Kenworthy & Mamajek, 2015b; Rieder & Kenworthy, 2016; Zanazzi & Lai, 2017a).

#### 6.14.7 Planetary oblateness due to rotation

In the solar system, planet rotation rates vary widely, reflecting their diverse formation and evolution (§12.4.5). Apart from close-in tidally-locked systems (§6.14.18), the same is likely to be true for exoplanets. A significant spin-induced planet oblateness (box, page 258) will then result in a slightly different light curve compared to that of a spherical planet of the same projected area.

Prospects for measuring a planet’s oblateness from transit photometry, and deriving the implied planetary rotation, have been variously considered (Hui & Seager, 2002; Seager & Hui, 2002; Barnes & Fortney, 2003; Ragozzine & Wolf, 2009; Carter & Winn, 2010b,a). Although the light curve of a transiting oblate planet should differ from that of a spherical one with the same cross sectional area under identical stellar and

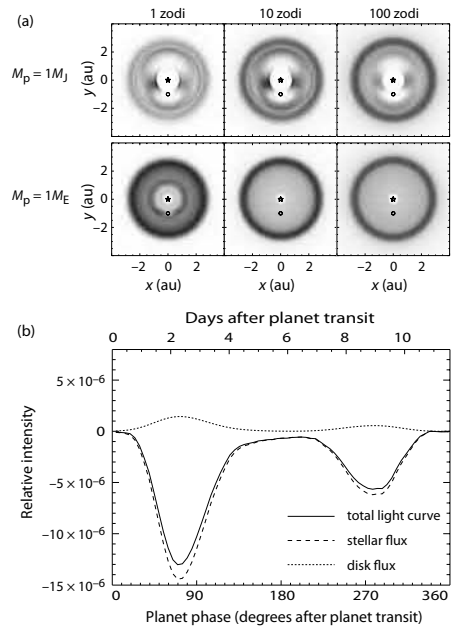


Figure 6.42: Models of the transit light curves of collisional exozodiacal clouds: (a) face-on optical depths for various models, as a function of planet mass (left), and maximum optical depth (top). Models assume scattering albedo  $\omega = 0.3$ , degree of forward scattering  $g = 0.5$ , and semi-major axis  $a_p = 1.0$  au. At optical depths  $\sim 100$  zodis, a  $1M_J$  planet can create significant resonant asymmetry, while an Earth-mass planet cannot; (b) light curve for a 10 zodi dust disk with  $\omega = 0.5$  and  $g = 0.8$ , perturbed by a  $1M_J$  planet on a circular orbit with  $a_p = 0.1$  au. Transiting dust clumps create the broad minima. The total light curve is the result of a competition between occulted stellar flux and forward-scattered flux from the disk. From Stark (2011, Figures 1–2), by permission of IOP Publishing/AAS.

orbital conditions, if the stellar and orbit parameters are unknown *a priori*, a global fit (to the stellar radius, planetary radius, impact parameter, and stellar limb-darkening) can largely mask the oblateness signature.

**HD 209458** Barnes & Fortney (2003) found, for example, that even if HD 209458 b had an oblateness of 0.1 (instead of their predicted 0.003), it would introduce detectable departures from a model spherical light curve at the level of only  $10^{-5}$ . Although planets with non-zero obliquity break this degeneracy, because their ingress and egress light curves are asymmetric, their best-case detectability was only of order  $10^{-4}$ . Neither is the measured rotation unique, due to a degeneracy between obliquity and oblateness, combined with the unknown component of obliquity along the line-of-sight.

**Quantitative description** The effect of oblateness can be quantified by calculating, at any moment across the transit, the intersection between the (elliptical) projection of the oblate planet and the (circular) projection of the star. The shape of an oblate planet can be described

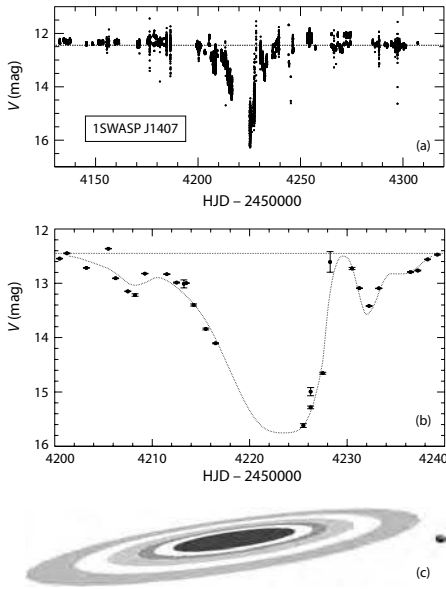


Figure 6.43: The transiting circumstellar/circumplanetary disk system 1SWASP J1407. (a) The eclipse was deep for  $\sim 14$  d, but accompanied at ingress and egress by a gradual dimming over  $\sim 54$  d. The dotted line indicates long-term median magnitudes outside of eclipse. (b) A non-unique model fitting the gross features of the nightly mean photometry. It comprises an orbiting object girded by a thick inner disk, a gap, and two ‘rings’ with a smaller gap between them. The ‘companion’ object has an orbital inclination of  $89^\circ.955$ , axial tilt with respect to the orbit plane of  $13^\circ$ ,  $P = 9862$  d ( $a = 8.7$  au), and radius  $R_c = 1.46R_J$ . The thick inner disk has optical depth  $\tau = 0.5$  and outer radius  $76R_c$ , a first ring has  $\tau = 0.2$  between  $106 - 127R_c$ , and a second ring has  $\tau = 0.05$  between  $128 - 163R_c$ . An additional outer ring is needed to fit dips outside the time interval shown. (c) Schematic of the dust disk model, with the K5 star J1407 shown to scale to the right. From Mamajek et al. (2012, Figures 4, 12, 13), by permission of IOP Publishing/AAS.

by the *flattening parameter* (or oblateness parameter)

$$f = \frac{R_{\text{eq}} - R_{\text{pol}}}{R_{\text{eq}}}, \quad (6.68)$$

where  $R_{\text{eq}}$  and  $R_{\text{pol}}$  are the equatorial and polar radii. The effective mean radius, viz. the radius of a spherical planet of the same cross sectional area, is given by  $R_p \equiv (R_{\text{eq}}R_{\text{pol}})^{1/2}$ . The planet’s obliquity,  $\theta$ , is the angle between the rotation axis of the planet and the orbital angular momentum vector (Carter & Winn, 2010b).

The flattening  $f$  is related to the rotation period  $P_{\text{rot}}$  of a planet with mass  $M_p$  by (Zhu et al., 2014b, eqn 2)

$$P_{\text{rot}} = 2\pi \left( \frac{R_{\text{eq}}^3}{GM_p(2f - 3J_2)} \right)^{1/2}, \quad (6.69)$$

where  $J_2$  is the quadrupole moment.

The true flattening and obliquity cannot be derived from the transit signature, but only their projected com-

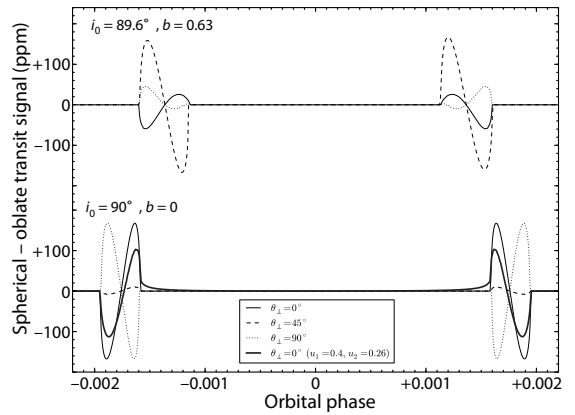


Figure 6.44: Example theoretical signals induced by an oblate planet with respect to a spherical planet of the same cross section, for  $\theta_{\perp} = 0, 45, 90^\circ$ , at  $b = 0.63$  (above) and  $b = 0$  (below). Signals are for a Jupiter-size ( $R_p/R_{\star} = 0.1$ ) planet with a Saturn-like oblateness ( $f_{\perp} = 0.1$ ). The curves are computed for stars with uniform surface brightness, except for the thick solid curve which is for a limb-darkened Sun-like star. From Zhu et al. (2014b, Figure 1), by permission of IOP Publishing/AAS.

ponents on the plane of the sky,  $f_{\perp}$  and  $\theta_{\perp}$ , such that the transit-derived oblateness represents only a lower limit on the true oblateness (Carter & Winn, 2010b).

The effect on the light curve is most pronounced during the ingress/egress phases for orbital inclination different from  $90^\circ$  and a non-zero projected obliquity (Seager & Hui, 2002; Barnes & Fortney, 2003; Zhu et al., 2014b). The theoretical maximum amplitude of the signal at the ingress/egress (compared to the non-oblate transit) is given by (Zhu et al., 2014b, eqn 3)

$$S_{\text{max}} \approx \frac{f_{\perp}}{2\pi} \left( \frac{R_p}{R_{\star}} \right)^2 = 160 \text{ ppm} \left( \frac{R_p/R_{\star}}{0.1} \right)^2 \left( \frac{f_{\perp}}{0.1} \right), \quad (6.70)$$

and the differences may reach  $1.5 \times 10^{-4}$  for rotational flattening similar to Jupiter and Saturn (Figure 6.44). Detectability of oblateness is maximised for planets transiting near impact parameter  $b \sim 0.7$ , regardless of obliquity (Barnes & Fortney, 2003).

**Observational constraints** Barnes et al. (2009a) used dynamical models of HD 209458 b and HD 189733 b to show that planet shapes resulting from rotation are unlikely to introduce detectable light curve deviations (below  $10^{-5}$  of the host star). Effects of oblateness on transit timing is considered in §6.19.

Carter & Winn (2010b) similarly found that for an optimal case of a transiting Jupiter with  $R_p/R_{\star} = 0.15$ , and a Saturn-like oblateness of 0.1, the maximum deviation between the transit signature of an oblate and a spherical planet is 400 ppm over the ingress and egress regions. HD 189733 b and other hot Jupiters with  $a \lesssim 0.2$  au, are expected to have spun down due to tidal dissipation, and to be tidally locked. Photometric signatures due



to oblateness from these slowly-rotating gas giants will likely be at the limit of current observability.

Carter & Winn (2010b) observed seven transits of the hot Jupiter HD 189733 b with Spitzer, ruling out a Saturn-like planetary oblateness.

Zhu et al. (2014b) selected a sample from the Kepler Q1–Q16 Catalogue with the following criteria:  $R_p < 2R_J$  to avoid eclipsing binaries;  $P > 15$  d such that the planet spin–orbit synchronisation time scale is  $> 250$  Myr; non-grazing transit ( $b < 0.8$ ) such that the transit system parameters are well constrained; and the expected S/N for a planet with a Saturn like oblateness is higher than 0.5 for a single transit. They identified 11 candidates, with only three having short-cadence data.

In addition to oblateness constraints  $f \lesssim 0.1 - 0.2$  for KOI–686 and KOI–197 (Kepler–489), and their control hot Jupiter HAT–P–7 b, Zhu et al. (2014b) reported a first tentative detection of an oblate planet (or brown dwarf),  $f = 0.22 \pm 0.11$ , for the  $18M_J$  Kepler–39 b.

**Transit depth variations** The effect of variations in transit depth caused by the spin precession of an oblate planet were considered by Carter & Winn (2010a). Biersteker & Schlichting (2017) attempted to measure these changes, using Kepler photometry, for the brown dwarf Kepler–39 b (unsuccessfully) and the warm Saturn Kepler–427 b. Transit depth variations for Kepler–427 b at 90% significance are consistent with precession period of  $5.45 \pm 0.4$  yr, and oblateness  $f = 0.19^{+0.32}_{-0.16}$ , comparable to the solar system gas giants.

#### 6.14.8 Atmospheric and topographic features

Light scattered by a planet with surface or cloud structures will vary in intensity and colour as the planet rotates, such that (changes in) the global planetary environment might be inferred from photometric transit observations. The large spatial scales of time-varying atmospheric structures, or ‘weather’, could generate significant photospheric variability. Studies have been made in the context of imaging missions, but should also be applicable to transit observations.

Models predict diurnal variations of a factor several, depending on ice and cloud cover, seasonal variations, surface composition (e.g. ocean versus land composition), atmospheric structures, and zonal winds (e.g. Ford et al., 2001b; Gaidos & Williams, 2004; Rauscher et al., 2007a; Pallé et al., 2008a; Williams & Gaidos, 2008; Barnes et al., 2009a; Oakley & Cash, 2009; Line & Parmentier, 2016). Inhomogeneous cloud cover has been inferred from planetary phase curves (§11.6.3), and corresponding transit asymmetries were unsuccessfully searched for in HAT–P–7, HD 209458, and Kepler–7 (von Paris et al., 2016a).

The different pathways for the formation of clouds and hazes (§11.4.1), combined with the expected atmospheric dynamics, is also expected to leave contrasting

signatures in the ingress and egress light curves (Line & Parmentier, 2016; von Paris et al., 2016a), and in the ingress and egress spectra (Kempton et al., 2017a).

The possibility of detecting lightning discharge events during transit has also been considered, and may be detectable in the case of HD 189733, and perhaps other identifiable systems if lightning intensity correlates (strongly) with volcanic activity (§11.4.1).

Prospects for determining exotopography (mountains, volcanoes, etc.) are considered by McTier & Kipping (2018).

#### 6.14.9 Night-side emission

While it is the day-side emission from irradiated planets that allows the detection of secondary eclipses (e.g. Figure 6.26), thermal emission from the planet’s night-side will also contribute to the primary transit light curve at infrared wavelengths (‘night-side ‘pollution’; Kipping & Tinetti, 2010). Allowing for this effect, the transit depth is no longer simply a function of  $R_p/R_*$ .

Given that the night-side emits flux with a contrast to the star’s emission of  $\sim 10^{-3}$  for hot Jupiters, the mid-infrared transit depth will be attenuated due to flux contribution from the night-side emission by  $\sim 10^{-4}$ . The effect can be compensated for if the full phase curve is measured, as with HD 189733 b (§6.15). Using archival Spitzer measurements, Kipping & Tinetti (2010) estimated that this night-side ‘pollution’ would be a 5–10 $\sigma$  effect for JWST.

#### 6.14.10 Early ultraviolet ingress and bow shocks

Wavelength-dependent transit depth variations probe the outer regions of the planet’s atmosphere (§6.24). An early transit ingress observed in the HST–COS near ultraviolet spectrum of the highly-irradiated WASP–12 b was initially attributed to the presence of a disk of previously stripped material (Fossati et al., 2010b). A model based on mass transfer by Roche lobe overflow, and leading to a mass loss from planet to star at a rate of  $10^{-7} M_J \text{ yr}^{-1}$ , was detailed by Li et al. (2010b).

Early ultraviolet ingress (in the C II doublet) was also reported for HD 189733 b by Ben-Jaffel & Ballester (2014), although not confirmed by Haswell et al. (2012).

An alternative explanation, put forward by Vidotto et al. (2010), is that the early ingress is caused by a (stellar-wind-driven) bow shock ahead of the planet, as observed in the solar system. For hot Jupiters, the bow shock will not form directly between the planet and the star, resulting in an asymmetric distribution of mass around the exoplanet, and hence an asymmetric transit profile. As the planet orbits through varying wind conditions, the strength and geometry of its bow shock will change, producing transits of varying shape (Vidotto et al., 2011b; Llama et al., 2011; Vidotto et al., 2011c).

Further modeling suggest that this explanation is less likely, or at least not for all cases (Alexander et al., 2016; Turner et al., 2016a).

Vidotto et al. (2010) derived an upper limit to the magnetic field of WASP-12 b of  $B_p \lesssim 2.4 \times 10^{-3}$  T, and concluded that shock formation leading to an observable early ultraviolet ingress is likely to be a common feature of transiting systems, placing constraints on planetary magnetic field strengths (Vidotto et al., 2011a; Llama et al., 2011), and their associated radio emission (Vidotto et al., 2012, see also Section 8.10.5).

Vidotto et al. (2011a) classified all transiting systems known at the time according to their potential for producing shocks that could cause observable light curve asymmetries. They found that 36 out of the 92 known transiting systems would lie above a reasonable detection threshold, and that the most promising candidates were WASP-19 b, WASP-4 b, WASP-18 b, CoRoT-7 b, HAT-P-7 b, CoRoT-1 b, TrES-3 and WASP-5 b. For prograde planets orbiting outside the corotation radius of rapidly-rotating stars, the shock position, rather than being ahead of the planet as in WASP-12 b, would trail the planet, resulting in a late-egress asymmetry. They identified CoRoT-11 b as such a late-egress candidate.

Despite a predicted timing difference of 5–11 min, near ultraviolet ground-based observations failed to detect an early ingress for TrES-3 (Turner et al., 2013). Near ultraviolet observations of 12 transiting planets with the Kuiper 1.55-m telescope, including CoRoT-1 b, showed no asymmetries (Turner et al., 2016b).

Llama et al. (2013) used magnetic maps of HD 189733 taken one year apart, coupled with a 3d stellar wind model, to determine the local stellar wind conditions throughout the planet's orbit. They predicted the time-varying geometry and density of the bow shock that forms around the planet's magnetosphere, finding that both the transit duration and ingress time can vary, providing diagnostics of the stellar wind.

An explanation attributed to a plasma torus associated with an exomoon, or possibly an accompanying Trojan satellite, is considered in Section 6.22.4.

#### 6.14.11 Refraction and stellar mirages

Light refracted by the planet's atmosphere is usually ignored in transit analyses. In practice, atmospheric refraction modifies the ingress and egress profiles, and leads to increased flux prior to ingress and subsequent to egress (Hui & Seager, 2002; Sidis & Sari, 2010; García Muñoz et al., 2012; Bétrémieux & Kaltenegger, 2014; Misra & Meadows, 2014; Dalba, 2017; Robinson et al., 2017). The effect is sometimes referred to as 'lensing' and, while not to be confused with gravitational lensing, leads to the existence of caustics tractable with a similar formalism (Hui & Seager, 2002; Dalba, 2017).

Although the effect is so far undetected in exoplanet

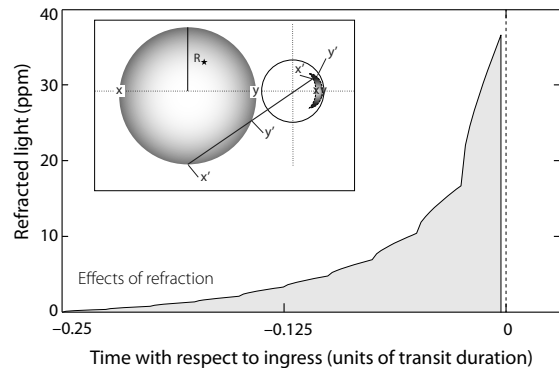


Figure 6.45: Effects of refraction on the pre-transit light curve for a 300 K Saturn-analogue orbiting a Sun-like star. Refraction leads to an increase in flux prior to ingress (and after egress). From Misra & Meadows (2014, Figure 1), by permission of IOP Publishing/AAS. The inset (adapted from Dalba, 2017, Fig. 1) shows the host star, exoplanet, and stellar mirage (dashed crescent) projected on the sky before or after transit (not to scale). Rays are traced in the equatorial plane of the star-planet system (inclined line). Labeled points on the star map to the secondary image in the exoplanet atmosphere as shown. The result is an inverted, distorted secondary image of the stellar disk.

transit light curves, it underlies Lomonosov's discovery of the Venusian atmosphere during the transit of Venus in 1761 (Cruikshank, 1983), is the subject of related studies of Venus (e.g. García Muñoz & Mills, 2012; Pere et al., 2016), and offers important future diagnostic probes.

For refraction effects to be observed, out-of-transit refracted light must be deflected by a large enough angle to be scattered into the beam to a distant observer. The characteristic angle of deflection is  $\sim R_*/d$ , where  $d$  is the planet-star distance. Accordingly, half a transit length prior to ingress, on the trailing side of the planet, light originating at the near and far stellar limb would have to be refracted by  $R_*/d$  and  $3R_*/d$  respectively, to reach a distant observer. More than half a transit length prior to ingress, the required refraction angles would increase, and closer to ingress they would decrease.

The effect may reach  $10^{-4}$  of the stellar light, measurable by current instruments, and providing estimates of the planet's atmospheric scale height (Sidis & Sari, 2010). For the atmospheric compositions considered by Misra & Meadows (2014), the maximum refracted signal was for a 300 K Saturn analogue orbiting a Sun-like star (Figure 6.45). For  $P_{\text{orb}} \gtrsim 70$  d, the transit width is determined by refraction, rather than by absorption.

**Other insights** In atmospheric transmission spectra, and in the absence of hazes, the Rayleigh scattering continuum slope yields the atmospheric scale height. Conclusions may be modified by refraction (Bétrémieux, 2016). In solar occultations of Saturn by Cassini-VIMS (§6.3.5), Dalba et al. (2015) found that refraction, as opposed to clouds or haze, determines the minimum altitude that could be probed during mid-transit.

Based on the code used to calculate refraction angles for

a suite of planetary atmospheres given by Misra et al. (2014b), Misra & Meadows (2014) showed that broad-band observations of refracted light in the out-of-transit spectrum could distinguish between a cloud- or haze-free atmosphere. Specifically, detection of refracted light pre-ingress and post-egress would preclude hazy atmospheres, because hazes tend to obscure those atmospheric layers that refract light. Detection could be accomplished in <10 h for Jovian exoplanets with JWST, and <5 h for super-Earths/mini-Neptunes with E-ELT, being most effective for planets with  $T_{\text{eq}} \sim 200 - 500$  K.

Modeling of transit spectra including the effects of refraction is detailed by Robinson (2017).

**Present constraints** In part due to Kepler's bias against long-period transits, Alp & Demory (2018) found no evidence for refraction features in the stacked Kepler light curves of 305 solar-like stars (their Figure 8), in agreement with their model predictions. Similar non-detections were reported by Dalba (2017).

**Stellar mirages** The unresolved increase in flux peaking just outside of transit encodes an inverted, distorted, but complete, secondary image of the host star, referred to by Dalba (2017) as a *stellar mirage*. In a detailed treatment, Dalba (2017) expands on the information contained in high-precision 'refraction' photometry, and details measurement prospects with Kepler/TESS and JWST. Insights may include quantifying the planet's atmospheric He content, a notoriously difficult species to measure remotely, but highly relevant to the evolution of gas giants. Effects are particularly pronounced in duration for non-transiting planets. Relevant targets include the long-period transiting discoveries expected from PLATO (§6.8.1), and from Gaia (§3.9.3).

**Algorithms** A publicly available out-of-transit refracted light model algorithm, RETr0, is described by Dalba (2017).

#### 6.14.12 Microlensing amplification

In systems with particularly massive or long-period planets, microlensing amplification of the stellar flux could be significant (Sahu & Gilliland, 2003; Agol, 2003). Compared with the 30–40 ppm photometric precision of Kepler, Sahu & Gilliland (2003) showed that for a solar-type primary transited by a white dwarf secondary, the maximum transit depth is 0.01%, which is almost entirely compensated for by the microlensing amplification when the white dwarf is at 0.05 au, and leads to a net amplification of 150 ppm at 0.1 au, and 2.4 mmag at 1 au. For brown dwarfs orbiting at a few au, the microlensing effect is several percent of the transit depth (§5.6.4).

For KOI-256, a mutually eclipsing post-common-envelope binary consisting of a cool white dwarf and an active M3 dwarf, Muirhead et al. (2013) showed that the size of the white dwarf with respect to the Einstein ring during transit causes the transit depth to be shallower than expected from pure geometry.

Perturbations to the Rossiter–McLaughlin effect are considered by Oshagh et al. (2013b, see also §6.18.3).

#### 6.14.13 Variability-induced motion

Variability-induced motion (VIM) arises in simultaneous astrometry and photometry when brightness variations in one component of a binary source or blended

image results in a correlated shift of the photocentre (Wielen, 1996). Exploiting space-based photometry and 1 mas-level astrometry, 288 stars in the Hipparcos Catalogue are classified as 'VIM' (Lindegren et al., 1997).

Coughlin et al. (2014) analysed the types of signal blends and contamination that can lead to detectable variability-induced motion in the Kepler data. Makarov & Goldin (2016b) processed the full long-cadence data, searching for astrometry and photometry correlations between quarters, and exploiting Kepler's single-measurement precision for photometry (20–40 ppm) and astrometry (< 1 mas for bright stars).

They identified significant variability-induced motion in 129 525 Kepler stars in at least one quarter. Of 7305 KOIs, 4440 were flagged at least once, of which 321 are 'confirmed', and a further 1946 are 'candidates'. Known variable stars and resolved binary stars have elevated rates. In addition to new eclipsing stars and superflares of solar-type stars, they suggest follow-up for other manifestations of transiting exoplanet systems.

#### 6.14.14 Grazing transits

Transits with large impact parameter will be particularly sensitive to changes in transit duration or transit shape. These changes may arise from orbit precession (e.g. due to an additional perturbing planet, or possibly exomoons or Trojans), stellar pulsations (affecting  $R_{\star}$ ), a non-spherical (rotating) planet, changes in limb darkening, or star spots close to their polar regions.

This sensitivity will be particularly marked in systems with *grazing transits*, in which only part of the planetary disk transits the host star's disk. The grazing condition is given, geometrically, by

$$g \equiv b + R_p / R_{\star} > 1, \quad (6.71)$$

where the impact parameter  $b$  is the projected distance between the planet and star centres during mid-transit in units of  $R_{\star}$  (Equation 6.19). In a grazing transit, the second and third contact points (box, page 154) are missing, the transit profile is v-shaped, the light curve solution is degenerate, and the system's physical properties are less well determined (§6.13.1).

Polarisation is also a sensitive function of the grazing condition (Kostogryz et al., 2015, see §6.17).

**Examples** Grazing transits include CoRoT-25 b (Almenara et al., 2013); CoRoT-33 b (Csizmadia et al., 2015); Kepler-16(AB) b (Doyle et al., 2011); Kepler-434 b (Almenara et al., 2015b); Kepler-447 b (Lillo-Box et al., 2015); K2-31 b (Grziwa et al., 2016); NGTS-1 b (Bayliss et al., 2018a); Qatar-6 b,  $g = 1.03$  (Alsubai et al., 2018); WASP-34 b,  $g = 1.016 \pm 0.015$  (Smalley et al., 2011a); WASP-45 b (Anderson et al., 2012); and WASP-67 b  $g = 1.07 \pm 0.04$  (Hellier et al., 2012; Mancini et al., 2014b).

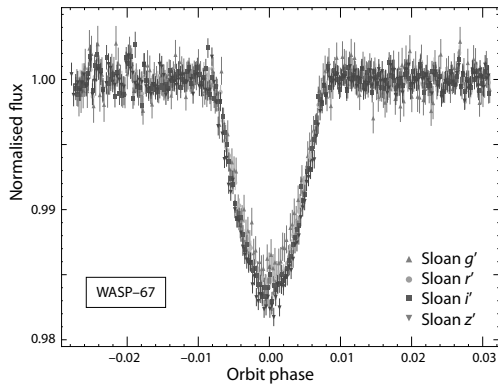


Figure 6.46: Multi-colour light curves of the grazing transit of WASP-67 b obtained with GROND, showing the v-shaped profile, and the change in transit shape with wavelength. The transit in  $g'$  is shallower than the other bands, since limb darkening is stronger at shorter wavelengths. From Mancini et al. (2014b, Figure 1), reproduced with permission © ESO.

Planets with near-grazing transits include HAT-P-14 b (Torres et al., 2010b); HAT-P-27 b, (Anderson et al., 2011a; Sada et al., 2012); OGLE-TR-56 (Adams et al., 2011a); TrES-2 (O'Donovan et al., 2006a); and TrES-3 (O'Donovan et al., 2007).

As examples, WASP-67 shows a prominent v-shaped transit profile, atypical of normal transit light curves, but characteristic of a grazing transit lacking second and third contacts (Figure 6.46). A similar v-shaped profile is seen for K2-31 b (Grziwa et al., 2016, their Figure 2).

**Time-varying effects** Within such systems, various associated time-varying effects have been considered.

Kepler-16 is an eclipsing binary system with component stars in an eccentric 41-d orbit (Doyle et al., 2011). A Saturn-mass planet is on a nearly circular 229-d circumbinary orbit, with the motion of all three bodies confined to within  $0.5^\circ$  of a single plane. As a result of the system's orbital evolution, planetary transits across star A should cease in early 2018, and return in 2042. Transits across star B are already grazing, and will disappear for 35 yr, beginning in 2014 May. Such 'transitional transits' are considered further in Section 6.19.8.

For TrES-2, the transits are almost grazing, and therefore again particularly sensitive to changes in orbital inclination. From a comparison of observations made in 2006 and 2008, Mislis & Schmitt (2009) detected an inclination change of  $0.1^\circ$ , corresponding to a transit duration change of 3.16 min, and attributable to a third, outer, non-transiting planet.

For GJ 436 b, the grazing incidence condition was invoked in the claimed discovery of planet c (Ribas et al., 2008), but this was subsequently considered as unconfirmed (Bean & Seifahrt, 2008; Coughlin et al., 2008).

**Paucity of systems** Since grazing transits are shorter, shallower, and often v-shaped, they can introduce an

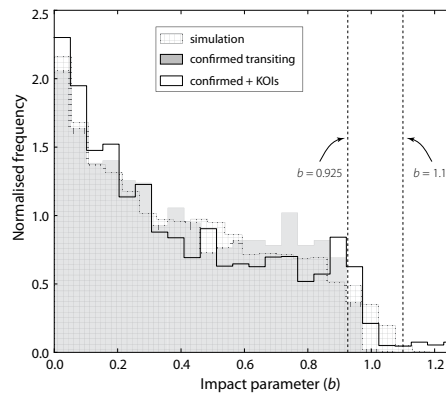


Figure 6.47: Grazing and near-grazing systems. Grazing systems ( $b \sim 1$ ) occupy the region between the dashed lines. Distributions show confirmed transiting planets (shaded), confirmed + KOI candidates (solid), and simulated (hatched). Near-grazing systems are significantly rarer than expected, perhaps due to perturbing effects of polar star spots. From Oshagh et al. (2015, Figure 2), reproduced with permission © ESO.

observational bias that leads to fewer being detected. Oshagh et al. (2015) compared the simulated numbers expected with those actually observed (Figure 6.47), suggesting a deficit in the numbers discovered to date.

Their favoured explanation, consistent with star spot models, is that many (nearly) grazing planets transit host stars with a (dark) giant polar star spot, and that the transit light curve degrades or vanishes due to the occultation of the grazing planet and the polar spot.

#### 6.14.15 Hill sphere transits

Between grazing and fully non-transiting systems lies the domain of a planet's *Hill sphere transit*, viz. transit of the region around the planet containing gravitationally bound circumplanetary material (see box, page 512). For some young evolving planets with known and extensive circumstellar structure in particular, a Hill sphere transit in principle provides a detailed probe.

**$\beta$  Pic b** From Gemini-GPI astrometry, Wang et al. (2016b) predicted such a Hill sphere transit for  $\beta$  Pic b, the young planet embedded in a near edge-on debris disk (§7.10.2), in 2017–18. Although the planet itself did not transit, the full Hill-sphere transit extended between ingress on 2017 April 3 and egress on 2018 January 29, and the 50% Hill sphere transit between 2017 June 20–November 12, with closest approach on 2017 August 31. The second half of the event was visible from most southern-hemisphere observatories, and an extensive monitoring campaign was scheduled. This included two dedicated stations, bRing, in S. Africa and Australia (Stuik et al., 2017), and a dedicated photometric monitoring nano-satellite, PicSat, launched on 2018 January 12 (Nowak et al., 2016).

While it was unknown in advance what, if anything, would be seen, possibilities included a circumplanetary disk or ring system comprised of residual material from planet formation, as observed around 1SWASP J140747.93–394542.6 by Kenworthy & Mamajek (2015b, see §6.14.6), or planetary satellites perhaps the size of Ganymede or Io (Wang et al., 2016b).

### 6.14.16 Planet–planet eclipses

In multi-transiting systems, especially those with short orbital periods, two or more planets may transit the star at the same time. Examples include K2–19bc (Armstrong et al., 2015b); TRAPPIST–1bc (de Wit et al., 2016b); WASP–47 (Becker et al., 2015); and the triple-transiting Kepler–11 bde (Lissauer et al., 2011a).

**Planet–planet transits** In a subset of these *double transit* events, a *planet–planet eclipse* or *mutual event* may occur, in which the inner transiting planet is itself occulted, partially or fully, by the outer planet. Possibilities were first studied in the context of binary planets or planet–moon systems (Cabrera & Schneider, 2007; Sato & Asada, 2009, 2010). Such mutual events during transit are also termed *planet–planet transits*, distinguishing them from planet–planet eclipses that may also occur outside of transit, where they have been termed *planet–planet occultations* (Ragozzine & Holman, 2010). By the end of 2017, the former phenomenon has been observed in one system (Kepler–89), and possibly in Kepler–51 (Masuda, 2014), while the latter has not.

Such mutual events allow for specific constraints on the physical and orbital parameters, and in particular the mutual inclination. Future planet–planet eclipses in the same system can also constrain their relative angular momentum, closely related to their orbital evolution (Masuda et al., 2013). They may even permit surface mapping with future telescopes (Luger et al., 2017a) and, yet more speculatively, they may offer configurations favourable for ‘eavesdropping’ on communicating civilisations (e.g. Guillochon & Loeb, 2015).

**Planet–planet occultations** As seen by a distant observer, planet–planet eclipses may also occur outside of transit (Figure 6.48). While analogous to transits, signals are orders of magnitude weaker, given the large star/planet surface brightness ratio. Events are relatively rare due to the low probability of disk overlap, and typically of short duration given the small planet sizes.

Compact co-planar multi-transiting systems like the 7-planet TRAPPIST–1 are particularly favourable (Veras & Breedt, 2017). Luger et al. (2017a) estimated some 1.4 occultations per day, with perhaps 10–20 per year of planets b and c detectable by JWST at 12–15  $\mu\text{m}$ .

**Syzygies** A planet–planet eclipse is a particular case of the general co-alignment of three (or more) bodies along the line-of-sight, or *syzygy*. This may occur not only for multiple transiting planets, but more generally also for triple or hierarchical stellar systems, circumbinary planetary systems (e.g. Kepler–1647, §6.26.3), planetary systems around one component of a binary, or systems with planetary companions (exomoons).

Various algorithms for computing the observed flux decrements and light curves for these arbitrary ‘overlapping’ events have been described, generalisations of

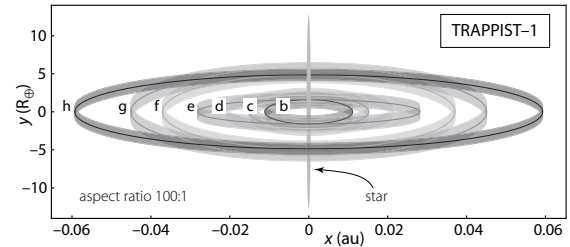


Figure 6.48: Orbits of the 7-planet TRAPPIST–1 system as seen from Earth, with an exaggerated 100:1 aspect ratio. The width of each orbital track is the planet diameter. Because of the system’s compactness, co-planarity, and near edge-on orientation, the orbital paths of all planets overlap with those of their neighbours over a significant fraction of their orbits. For this particular configuration, planet–planet occultations occur between the set of planets {b, c, d, e} and the set {f, g, h}. From Luger et al. (2017a, Figure 1), by permission of IOP Publishing/AAS.

those used for single-planet cases (Mandel & Agol, 2002; Giménez, 2006a; Pál, 2008, see also §6.13.2). They include triple star systems (Carter et al., 2011a), planet–moon transits (Kipping, 2011a), and planet–planet transits (Pál, 2012; Veras & Breedt, 2017).

In more realistic cases, where the sky projection of the star and/or planet is an ellipse (due to rotational flattening or tidal distortion) or for more complex models (including limb darkening, stellar activity, or limb polarisation), Monte Carlo integrations can be used (e.g. Press et al., 2007). A fast and stable implementation is given by Carter & Winn (2010b, their Appendix A).

Code to calculate geometric probabilities for planet–planet occultations and mutual transits is given by Brakensiek & Ragozzine (2016).

**Kepler–89** Hirano et al. (2012a) discovered a planet–planet transit in the four-planet system Kepler–89 (KOI–94). During this event, part of the inner planet, Kepler–89 d, is itself occulted by the outer transiting planet, Kepler–89 e (Figure 6.49a–b).

The duration of the eclipse event depends sensitively on the mutual orbit inclination  $\Delta i$ , which is therefore well constrained by the mutual occultation profile (the other free parameters being the mid-transit times, and the limb-darkening). Hirano et al. (2012a) derived  $\Delta i = -1.15 \pm 0.55^\circ$ , implying that the two orbital planes are well aligned.

Planet masses and eccentricities, initially derived from radial velocities with Keck–HIRES (Weiss et al., 2013), were improved by Masuda et al. (2013) based on transit time variations (Figure 6.49c). Specifically, the standard parameters from the transit light curves ( $t_0$ ,  $P$ ,  $R_p/R_\star$ ,  $b$ ,  $u_1$ ,  $u_2$ ), are complemented by those from the transit time variation analysis ( $M_p$ ,  $e$ ,  $\tilde{\omega}$ ). The transit time variation of Kepler–89 c shows modulation with period  $(1/P_c - 2/P_d)^{-1} \approx 155$  d, arising from the near 2:1 resonance of planets c and d (Xie et al., 2014).

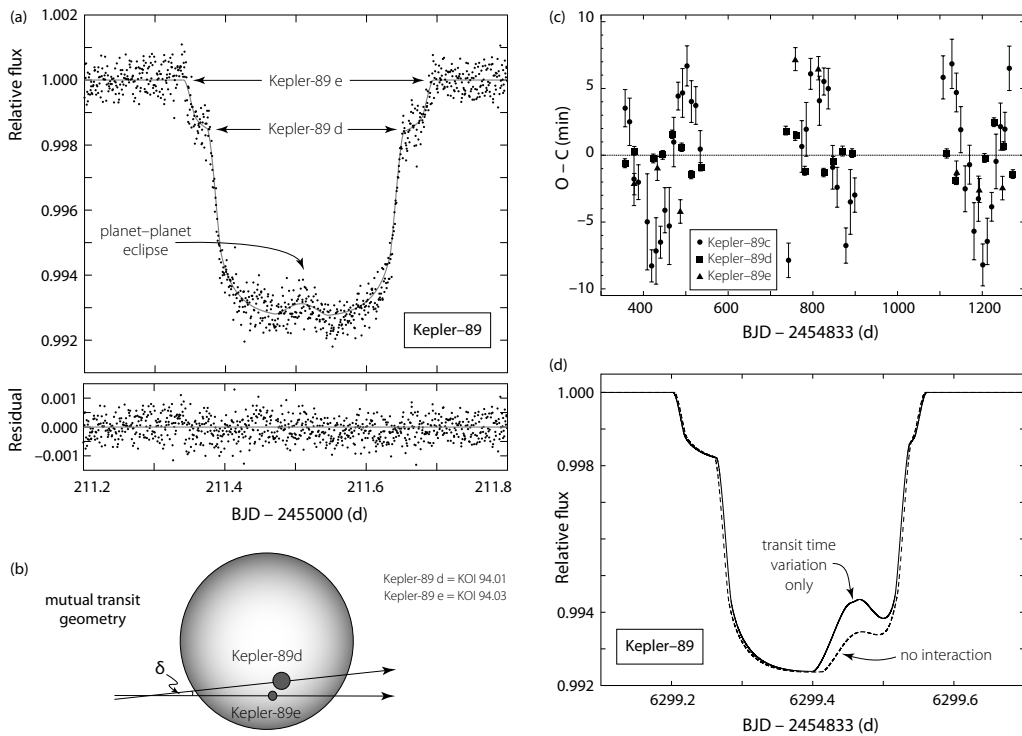


Figure 6.49: The 4-planet system Kepler-89 (KOI-94), and the planet-planet mutual occultation: (a) part of the Kepler light curve showing the simultaneous two-planet transit event. A first (shallow) transit (Kepler-89 e  $\equiv$  KOI-94.03) starts around BJD = 2 455 211.35, followed by a second, deeper dimming (Kepler-89 d  $\equiv$  KOI-94.01). A bump around the transit centres is the planet-planet eclipse; (b) schematic (not to scale) illustrating the mutual inclination  $\delta$  between the projected orbits of planets Kepler-89 d and Kepler-89 e; (c) observed transit time variations of Kepler-89 c-e; (d) predicted light curve for the double transit which will occur on 2026 April 1/2, showing the sensitivity of the planet-planet eclipse profile to the ephemeris model. The lower dotted curve, with a less pronounced bump, results from a non-interacting planet model, while the solid line is for the dynamically-interacting transit time variation model. Left pair (a-b) from Hirano et al. (2012a, Figure 2), by permission of IOP Publishing/AAS. Right pair (c-d) from Masuda et al. (2013, Figures 5 and 15), by permission of IOP Publishing/AAS.

Masuda et al. (2013) also derived an expression for their mutual inclination,  $\Omega_{21}$ , based on the three observables (height, epoch, and duration) of the brightening ‘bump’ due to the planet-planet eclipse. Collectively, these allow prediction of the epoch and profile of the next planet-planet eclipse on 2026 April 1/2, which will be more pronounced, and will further constrain the mass of planet d (Figure 6.49d).

#### 6.14.17 Tidal effects

Tidal effects (§10.11) distort the light curves and may also result in detection biases. For  $P \lesssim 3 - 5$  d, Pont (2009) found that, in order of increasing mass, close-in planets will be tidally unaffected ( $M \ll M_J$ ), circularised ( $M \approx M_J$ ), spiraling in ( $M \approx 1 - 2M_J$ ), destroyed ( $M \approx 2 - 3M_J$ ), and synchronised ( $M \gtrsim 3M_J$ ). Host stars which are rapidly rotating as a result of tidal spin-up may be dropped from Doppler searches due to their broadened spectral lines, and due to the expected correlation between spin rate and photospheric activity.

Rotation-induced variability coupled with very short-period transits may also lead to transit light curves qualitatively different from those assumed in standard transit searches (Figure 6.50), resulting in a detection bias against massive close-in planets for transit surveys. Such a system would be represent an extreme form of reflected light and ellipsoidal variations, discussed further in Section 6.15.3.

Other manifestations of tidal effects are detailed in the following sections, specifically the effects of planetary oblateness as a result of tidal locking (§6.14.18), tidally-induced gravity darkening (§6.14.19), tidally-induced stellar oscillations (§6.14.20), tidal disruption (§6.14.21), and evidence for disintegration (§6.14.22).

#### 6.14.18 Planetary prolateness under tidal locking

Around half of the more than 3000 known transiting exoplanets have  $P \lesssim 10$  d. These close-in planets undergo strong tidal effects raised by the host star, with the consequence that their spin rates and orbits evolve until

**Solar system syzygies:** Exoplanets orbiting at  $\sim 1$  au will be challenging to detect from their periodic transit signal alone, due to their long orbital periods. *Simultaneous transits* of two such planets will be improbably rare.

Compounded by the orbital motion of the Earth, transits of Mercury occur only 13 or 14 times per century. Transits of Venus occur in a repeating pattern every 243 yr, with pairs eight years apart, separated by gaps of over a century. The most recent pair were on 2004 June 8 and 2012 June 6 and, before that, in December 1874 and December 1882.

According to Meeus & Vitagliano (2004), simultaneous transits of Mercury and Venus seen from Earth last occurred on 373 173 September 22 BCE, and will next occur on 69 163 July 26, and thereafter only in 224 508 March. A simultaneous transit of Venus and Earth will be visible from Mars in the year 571 741 CE.

The first recorded planet–planet occultation was that of Jupiter by Mars in 1170 CE, observed by the monk Ger vase of Canterbury, and by Chinese astronomers (Hilton et al., 1988; Luger et al., 2017a). Albers (1979) computed ephemerides of past and future occultations, finding two in the 19th century, none in the 20th, and five in the 21st century, all involving one of Mercury and Venus, and one of the *superior planets* (those beyond Earth).

Occultations among solar system moons also occur. LBT interferometric thermal imaging of an occultation of Io by Europa in 2015 March yielded high resolution ( $\sim 2$  km) maps of Io’s volcano Loki Patera (de Kleer et al., 2017).

Triple transits of Jupiter’s Galilean moons occur once or twice per decade: the crossings of Callisto, Io and Europa were observed by HST–WFC3 on 2015 January 24.

an equilibrium configuration is reached, corresponding to co-planarity, circularity, and (generally) synchronous rotation (§10.11).

Under these conditions, their shape will differ from that of a spherical body, approximated better by a triaxial ellipsoid (§10.11.11). The asymmetry in the mass distribution increases with the proximity to the star, and it is particularly pronounced near the Roche radius (e.g. Ferraz-Mello et al., 2008; Burton et al., 2014). The effect may be significant for rocky planets as well as gas giants, especially those orbiting M dwarfs (Saxena et al., 2015).

Distortion of an object’s spherical shape has long been known to provide insight to its interior structure, composition and evolution, both for gas giants (e.g. Chandrasekhar, 1933a,b; Lai et al., 1993) as well as solid solar system bodies (e.g. Dermott, 1979).

The resulting equatorial prolateness for close-in exoplanets can be pronounced although, since the long axis always points to the star, it is not perceptible during the transit. Ignoring this distortion results in a systematic underestimation of the planetary radius, and hence of its bulk density. In addition, and especially for the increasing number of transiting planets being detected near the Roche radius, and therefore on the verge of tidal disruption (e.g. Valsecchi & Rasio, 2014a), the projected ellipsoid shape depends sensitively on the orbit inclination and obliquity.

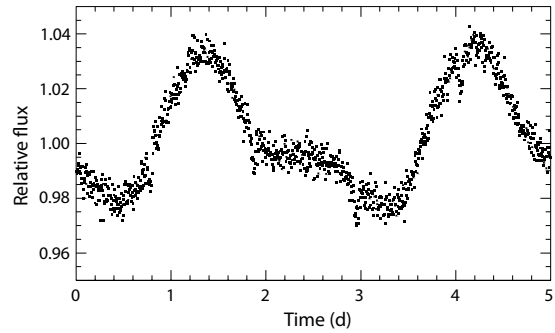


Figure 6.50: Simulated transit light curve of an imaginary planet with  $P \sim 0.9$  d and  $M \sim 2M_J$ , illustrating the very different light curve that may result from a planet which has spiraled inwards imparting significant angular momentum to a solar-type host star. Data points with 6 min sampling have been extrapolated from the light curve of CoRoT–2. The simulation is an extreme example of the form seen in Figure 6.59. From Pont (2009, Figure 7), © Oxford University Press.

Assessments of the effect have been made by Leconte et al. (2011) based on internal structure models, by Burton et al. (2014) who determined tidal deformation assuming surfaces of constant gravitational equipotential solely based on observable parameters, and by Correia (2014) who proposed a simple analytical model to compute the projected area of close-in planets at any point of its orbit, which is based in the equilibrium surface given by second-order Love numbers. Theoretical transit light curves can be used to compare directly with the observations, and infer their internal structure and density. The following is an outline of the formulation given by Correia (2014).

**Planet shape** The figure (shape) of the planet is described in Cartesian coordinates by a reference triaxial ellipsoid

$$\frac{X^2}{a^2} + \frac{Y^2}{b^2} + \frac{Z^2}{c^2} = 1, \quad (6.72)$$

where  $a$ ,  $b$ , and  $c$  are the semi-principal axes. For the Earth and the gaseous planets in the solar system,  $a \approx b > c$  (oblate spheroids), while for the main satellites (typically)  $a > b > c$ , with the long axis  $a$  directed towards the parent planet.

For  $a \sim b \sim c$ , the ellipsoid can be approximated by

$$R = X^2 + Y^2 + Z^2 \approx b + \frac{f_a}{b} X^2 + \frac{f_c}{b} Z^2, \quad (6.73)$$

where  $f_a = (a - b)/b$  and  $f_c = (c - b)/b$ . The mass distribution results from the planet’s self gravity, combined with its deformation under any perturbing potential  $V_p$ .

A convenient way to characterise this deformation is through *Love numbers* (Love, 1911), which relate the radial displacement  $\Delta R$  to  $V_p$  through

$$\Delta R = -h_f V_p / g, \quad (6.74)$$

where  $g = GM_p/R^2$  is the surface gravity, and  $h_f$  is the fluid (second) Love number. For a homogeneous sphere  $h_f = 5/2$ . More generally, it is given by the Darwin–Radau equation (e.g. Jeffreys, 1976)

$$\frac{I}{M_p R^2} = \frac{2}{3} \left[ 1 - \frac{2}{5} \left( \frac{5}{h_f} - 1 \right)^{1/2} \right], \quad (6.75)$$

where  $I$  is the mean moment of inertia, which depends on the internal mass differentiation.<sup>1</sup>

As for the main satellites in the solar system, close-in planets deform under the action of both centrifugal and tidal potentials. The former is a consequence of the body's rotation rate about the  $c$  axis,  $\Omega$ , while the latter results from the (differential) gravitational attraction by the nearby star.

For a planet in tidal equilibrium, in a circular orbit of radius  $r_0$ , the spin axis is normal to the orbit plane, and the rotation rate is synchronous with the orbital mean motion  $n$ , with the long axis  $a$  pointing towards the star. On the planet's surface, the non-spherical component of the perturbing potential is

$$V_p = \frac{1}{2} \Omega^2 Z^2 - \frac{3GM_\star}{2r_0^3} X^2. \quad (6.76)$$

Replacing this perturbing potential in Equation 6.74, and comparing with Equation 6.73

$$\frac{f_a}{b} = h_f \frac{3GM_\star}{2gr_0^3}, \quad (6.77)$$

$$\frac{f_c}{b} = -h_f \frac{\Omega^2}{2g}, \quad (6.78)$$

where  $\Omega^2 = n^2 \approx GM_\star/r_0^3$ . These can be re-written

$$a = b(1 + 3q), \quad (6.79)$$

$$c = b(1 - q), \quad (6.80)$$

with

$$q = \frac{h_f}{2} \frac{M_\star}{M_p} \left( \frac{b}{r_0} \right)^3. \quad (6.81)$$

The difference between the ellipsoid semi-axes therefore has a  $r_0^{-3}$  dependency on the star–planet separation. The maximum value of  $q$  corresponds to the Roche radius,  $R_R$  (Chandrasekhar, 1969)

$$r_0 \geq R_R \equiv 2.46 \left( \frac{M_\star}{M_p} \right)^{1/3} b \Rightarrow q < q_{\max} \approx \frac{h_f}{30}. \quad (6.82)$$

Adopting the maximum value of  $h_f = 5/2$  (Equation 6.74) gives  $q_{\max} \approx 0.08$ ,  $a_{\max} \approx 1.25b$ , and  $c_{\max} \approx 0.92b$ .

<sup>1</sup>There are other methods that allow indirect determination of the Love number (e.g. Batygin et al., 2009a; Ragozzine & Wolf, 2009; Mardling, 2010), but they require knowledge of the global system dynamics, e.g. via the presence of planetary companions, along with precise eccentricities and inclinations.

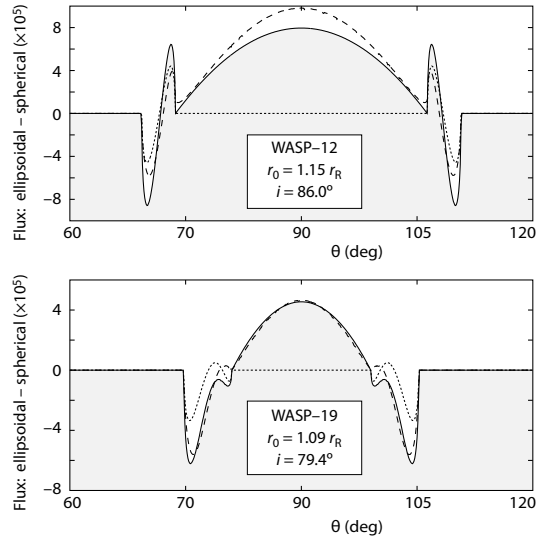


Figure 6.51: Difference between the theoretical transit light curves for a spherical planet, and various ellipsoidal models, for the two close-in planets WASP-12 and WASP-19.  $r_0$  is the star–planet separation in units of the Roche radius,  $r_R$ . The solid line is for the tidally distended (equatorially oblate) model (Equation 6.83). The dashed line includes stellar limb darkening. The dotted line is for an oblate planet with  $a = b \neq c$ . From Correia (2014, Figure 1), reproduced with permission © ESO.

In Cartesian coordinates centred on the star, with  $(x, y)$  in the plane of the sky and  $z$  along the line-of-sight, the projection in the  $(x, y)$  plane reduces to

$$A(x - x_0)^2 + B(x - x_0)(y - y_0) + C(y - y_0)^2 = 1, \quad (6.83)$$

with

$$A = \cos^2 \theta / a^2 + \sin^2 \theta / b^2, \quad (6.84)$$

$$B = (1/a^2 - 1/b^2) \sin 2\theta \cos i, \quad (6.84)$$

$$C = (\sin^2 \theta / a^2 + \cos^2 \theta / b^2) \cos^2 i + \sin^2 i / c^2.$$

The stellar flux decrement is then given by the overlap between the planetary ellipse (Equation 6.83) and the (spherical) stellar disk

$$x^2 + y^2 = R_\star^2. \quad (6.85)$$

**Resulting transit light curve** Figure 6.51 shows the difference between the theoretical transit light curves for a spherical planet, and various ellipsoidal models, for two of the 16 close-in planets considered by Correia (2014), WASP-12 and WASP-19. The spherical radius is chosen such that its area is equal to the projected ellipse area just after second contact. The three ellipsoidal models correspond to the tidally distended (equatorially oblate) model given by Equation 6.83, to the same model but including stellar limb darkening and, for comparison, to an oblate planet with  $a = b \neq c$  (cf. Seager & Hui, 2002; Barnes & Fortney, 2003; Carter & Winn, 2010b).



There are two main differences between the ellipsoidal and spherical cases. The signature around transit ingress and egress is attributable to the polar oblateness, as identified in previous studies and described further in Section 6.14.7 (cf. Figure 6.44). The second feature corresponds to difference over the entire transit, due to the rotation of the tidally distorted planet.

Since the projected ellipsoid only depends only on  $q$  (and  $b$ ),  $q$  is the only supplementary parameter in the light curve fit. In turn, in the expression for  $q$  (Equation 6.81), all parameters except  $h_f$  are known from the observational data. Observation of the effect would provide an estimate of  $h_f$ , and an additional constraint for the inner structure differentiation (Equation 6.75).

Flattening predictions for 469 planets with known mass, radius and orbital period were estimated, under two assumptions (of tidal locking and fixed rotation period of 10.55 h), were made by Zhang & Huang (2017).

**Effect on densities** Assumptions of a spherical planet, and the associated volume  $V_p = 4\pi R_p^3/3$ , provide a spherical bulk density estimate. For close-in planets, the volume of the tidally-distorted ellipsoid is more accurately given by  $V' = 4\pi abc/3$ , which gives for the true bulk density

$$\rho'_p = \frac{3M_p}{4\pi abc} \approx \frac{3M_p}{4\pi b^3} (1 - 2q). \quad (6.86)$$

For the 16 close-in planets near the Roche radius studied by Correia (2014), density corrections reach 20% for rocky planets, and 15% for gas giants, with corrections increasing with decreasing star–planet separation.

#### 6.14.19 Tidally-induced gravity darkening

Various modifications to the transit light curves arise from star–planet tidal interactions. These include geometrical projection effects arising from the perturbed figures of the star (§6.14.3) and planet (§6.14.18). Outside of the transit and eclipse phases, the distorted (approximately ellipsoidal) figure of the star also results in photometric modulation of the orbital light curve as a consequence of the star’s changing projected area and surface brightness (§6.15.5).

A more subtle manifestation results from *gravity darkening* of the stellar surface. As described by Jackson et al. (2012b), the planet’s tidal gravity perturbs the balance of forces (pressure, the star’s own gravity, and radiation) within the stellar atmosphere, and results in a small (few 0.1 K) decrement in  $T_{\text{eff}}$  and brightness on the stellar surface nearest the planet. The phenomenon is similar to that of (stellar) rotationally-induced gravity darkening (§6.14.3). The reduction in stellar surface temperature results in a slight reduction in luminosity, and a ‘darkened patch’ on the stellar surface.

**Predictions** Jackson et al. (2012b) parameterised the gravity darkening in terms of the surface gravity (their eqn 7), along

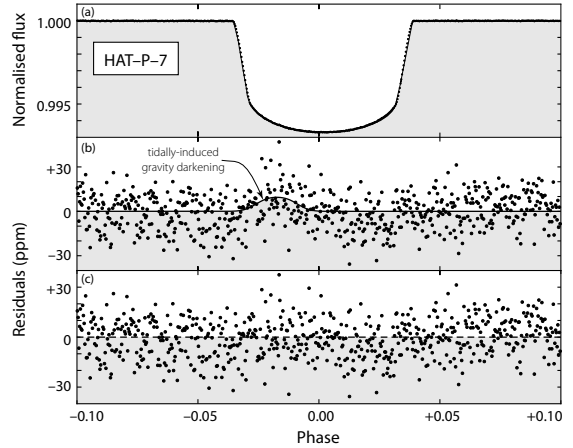


Figure 6.52: Planet-induced gravity darkening in the transit light curve of HAT-P-7, from Kepler Q1–Q9 (326 transits). Data cover  $\pm 0.1$  in phase centred on mid-transit, in 1 min bins: (a) composite light curve, with error bars omitted; (b) residuals after removing the best-fit ‘standard’ light curve. The solid curve shows the best-fit model for a planetary transit crossing the gravity-darkened spot on the stellar surface; (c) residuals after including the gravity-darkened model. From Morris et al. (2013, Figure 1), by permission of IOP Publishing/AAS.

with  $T_{\text{eff}}$  on the stellar surface (their eqn 10). They also noted that tides raised by planets have a negligible effect on the mean stellar  $T_{\text{eff}}$ , such that the usual distinctions between a star’s polar and mean effective temperatures (Wilson, 1994) are unimportant. They predicted that, with very high accuracy photometric data and a planet inducing a large perturbation, the effect could be observed as an eclipse of the darkened stellar patch by the planet during a transit. Since HAT-P-7 is one of the brightest Kepler targets, it represented a favourable target.

**HAT-P-7** Such *planet-induced gravity darkening* was duly observed for HAT-P-7 by Morris et al. (2013). They analysed two years of Kepler data (326 transits and 355 eclipses), and identified a marginal brightening, of  $\sim 10$  ppm, during the transit, and just prior to the mid-transit time (Figure 6.52). They excluded effects attributable to star spots (due to the effect’s persistence), or to rotationally-induced gravity darkening (due to the star’s slow rotation). They favoured a model in which stellar tidal distortion due to the planet (at  $a \sim 4R_*$ ) causes a decrease in surface gravity near the sub-planet region, moving with the planet, and results in a local decrease in stellar surface brightness.

Fitting a ‘cool spot model’ to the transit light curve residuals (Figure 6.52), they determined a temperature difference between the darkened spot and the mean stellar surface of  $\Delta T = -0.18$  K, and a phase lag from the sub-planet point on the stellar surface of 0.06 ( $\sim 3$  h).

The hypothesis is supported by their estimate of the time between the passing of the planet and of the dark spot through the sub-observer point,  $\Delta t$ , determined by how rapidly the stellar atmosphere can react to the gravitational perturbation of the passing planet (in turn determined by the sound speed in the photosphere)

$$\Delta t \sim \frac{H}{c_s} \sim \sqrt{\frac{3kT}{5\mu m_{\text{H}}g^2}}, \quad (6.87)$$

**Tidally-excited oscillations and heartbeat stars:** Tidally-excited oscillations in stellar binaries are known to occur through resonant excitation by dynamical tides (e.g. Cowling, 1941; Zahn, 1975; Kumar et al., 1995; Aerts et al., 2010). Only a few examples were known pre-Kepler, their rarity being due to the fact that the forcing frequencies must be very close to the free eigenmodes of one of the stars in order to resonantly excite the oscillation. This leads to the excitation of gravity modes whose frequencies are, in turn, exact multiples of the orbit frequency (Willems, 2003).

The first two such systems found are single-line spectroscopic binaries, HD 177863 (De Cat et al., 2000) and HD 209295 (Handler et al., 2002), both discovered from ground-based photometry and spectroscopy. An eclipsing double-lined spectroscopic binary example, HD 174884 ( $e = 0.29$ ,  $P_{\text{orb}} = 3.66$  d), was discovered with CoRoT, and has pulsations at 2, 3, 4, 8, and 13 times the orbital frequency (Maceroni et al., 2009).

The fourth, KOI-54 (HD 187091), discovered from Kepler photometry, is a high-eccentricity ( $e = 0.83$ ) stellar binary (Welsh et al., 2011; Fuller & Lai, 2012; Burkart et al., 2012). Persistent pulsations arise as resonances between the dynamical tides and the free oscillation modes of one or both of the stars. In addition, KOI-54 shows sharp periodic brightening every 41.8 d (Figure 6.53).

KOI-54 is now considered to be the prototype of the class of so-called *heartbeat stars*. These display near-resonant tidally-excited pulsations of constant amplitude throughout the orbit, as well as a characteristic periodic light curve, induced by close pericentre passage in a high-eccentricity binary, and which result from a combination of tides, heating, and Doppler beaming. Some 200 have been found from Kepler (Thompson et al., 2012; Beck et al., 2014; Shporer et al., 2016; Hambleton et al., 2016; Dimitrov et al., 2017; Guo et al., 2017b).

where  $H$  is the atmospheric scale height,  $c_s$  is the sound speed, and the second expression invokes the perfect gas equation of state with temperature  $T$  and surface gravity  $g$ , estimated from stellar atmosphere models. Their prediction,  $\Delta t \sim 1.02 \times 10^4$  s, is in agreement with the observed phase lag,  $\Delta t \sim 1.06 \times 10^4$  s.

#### 6.14.20 Tidally-excited stellar oscillations

The planet-hosting  $\delta$  Scuti star WASP-33 was the first system in which stellar oscillations have been attributed to tidal excitation by a close-orbiting planet (Collier Cameron et al., 2010b; Herrero et al., 2011). These are analogous to tidally-excited oscillations seen in stellar binaries (box, page 230). Planet-induced stellar oscillations were also attributed to the  $e = 0.5$  HAT-P-2 b from 350 h of  $4.5 \mu\text{m}$  Spitzer photometry (de Wit et al., 2017).

#### 6.14.21 Tidal disruption

Most hot Jupiters are expected to spiral in toward their host stars because the angular momentum of the orbital motion is transferred to the stellar spin, leading to a progressive shift in transit times (§6.19.6). The end result of this process is some combination of tidal disruption, disintegration, and engulfment of the planet.

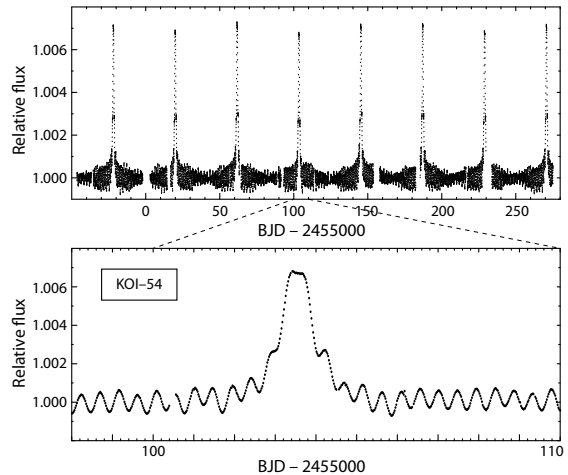


Figure 6.53: Top: Kepler light curve of the eccentric binary ‘heartbeat’ star KOI-54. Bottom: details of a brightening event. Pulsations arise as resonances between dynamic tides at pericentre, and the free oscillation modes of one or both of the stars. While KOI-54 is not accompanied by known planets, analogous tidally-excited stellar pulsations by an orbiting planet have been suggested for WASP-33, and for HAT-P-2. From Welsh et al. (2011, Figure 1), by permission of IOP Publishing/AAS.

The hydrodynamical modeling of Faber et al. (2005) focused (only) on a planet’s first close stellar fly-by. Guillochon et al. (2011) extended this to multiple passages of a Jupiter-like planet by a Sun-like star, assessing the planet’s survival prospects as a result of prolonged tidal forcing over many orbits.

**Period distribution** The orbital period distribution of gas giants places constraints on their formation, migration, and future evolution. The majority of hot Jupiters ( $a < 0.1$  au), are found in a ‘pile-up’ at periods of  $P \sim 3 - 4$  d ( $a = 0.035 - 0.045$  au), with only a small number found in very close-in orbits ( $a < 0.02$  au,  $P < 1$  d).

The sharp decline in numbers at very short periods is seen in both ground-based (e.g. SuperWASP, Hellier et al., 2012) and space-based (Kepler, e.g. Howard et al., 2012b) searches, indicating that it is either difficult to get gas giants into very close orbits, or that they are quickly destroyed by strong tidal forces once they arrive (Guillochon et al., 2011; Valsecchi & Rasio, 2014a). The latter would imply that very close-in hot Jupiters with old host stars are in the last few per cent of their lifetimes.

Guillochon et al. (2011) found that: (a) planets scattered into close-approach orbits less than about three times the tidal radius,  $r_t = R_p (M_\star / M_p)^{1/3}$ , are either destroyed or completely ejected from the system; (b) many hot Jupiters have a maximum initial apocentre for scattering that lies well within the ice line (implying that they must have migrated either before or after the scattering event); (c) the disruption and/or ejection of Jupiter-mass planets deposits  $\sim 1 J_\odot$  of angular momentum onto

the host star; and (d) for systems in which planet–planet scattering is common, planetary hosts have up to a 35% probability of possessing an obliquity relative to the invariable plane of  $> 90^\circ$ .

The orbit evolution of giant planets due to tidal dissipation is poorly constrained by observations. The efficiency of the dissipation of orbital energy due to frictional processes in the star is usually parameterised by the stellar tidal quality factor  $Q'_\star$  (§10.11). Studies of binary star systems suggest  $Q'_\star \sim 10^6$ , while analyses of the tidal evolution of hot Jupiters yield comparable estimates, for example  $10^6 < Q'_\star < 10^9$  by Jackson et al. (2008b), and  $Q'_\star \gtrsim 10^7$  by Penev et al. (2012).

There are no direct determinations of  $Q'_\star$  from the observation of a decaying orbital period. Observational constraints on the systematic evolution in transit times are detailed in Section 6.19.6.

**Proximity to tidal disruption** The shortest-period hot Jupiters are in orbits just beyond their tidal destruction radius, viz., the critical separation inside which the planet would lose mass via Roche lobe overflow,  $a_{\text{Roche}} \sim 2.16R_p(M_\star/M_p)^{1/3}$  (§6.22.1).

Mass-loss through Roche lobe overflow may affect their evolution, possibly transforming a hot Jupiter into a lower mass hot Neptune or super-Earth (with rocky cores and depleted envelopes) in orbits of a few days (e.g. Valsecchi & Rasio, 2014b; Valsecchi et al., 2014, 2015; Jackson et al., 2016, 2017b), with the mass lost in eccentric systems being either re-accreted by the planet, directly impacting the stellar surface or forming a disk around the star (Dosopoulou et al., 2017). Associated prospects for determining the core mass of hot Jupiters are detailed by Ginzburg & Sari (2017a).

Continuing tidal decay, with estimated orbital time scales  $\lesssim 1$  Gyr in the case of HAT-P-36 and WASP-19 (Essick & Weinberg, 2016), and perhaps as short as  $\sim 10^5 - 10^6$  yr for KELT-16 (Oberst et al., 2017), may lead to detectable transit timing variations, and may explain the paucity of Jupiter-mass planets with  $P \lesssim 2$  d (§6.28).

There are 7 transiting planets with  $P < 1$  d and  $M_p > 1M_J$ : HATS-18 b, K2-22 b, KELT-16 b, WASP-18 b, WASP-19 b, WASP-43 b, and WASP-103 b. As examples of the associated phenomena, WASP-43 b is a well-studied prototype for these ultra-short period highly-irradiated giant planets; HATS-18 b is inferred to be in the process of spinning up its host star (Penev et al., 2016); K2-22 b is inferred to be a disintegrating rocky planet with a cometary head and leading tail (Sanchis-Ojeda et al., 2015a, §6.14.22); and KELT-16 b orbits at 1.7 Roche radii and, depending on  $Q'_\star$ , could be tidally disrupted in as little as a few  $10^5$  yr (Oberst et al., 2017).

Other short-period systems have been explicitly noted as being close to tidal disruption, amongst them WASP-121 (Delrez et al., 2016).

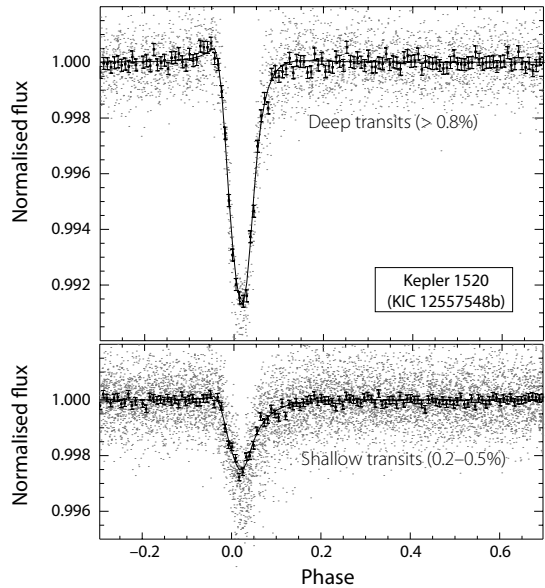


Figure 6.54: Light curves of the disintegrating planet Kepler-1520 b, binned in 0.008 in phase. The upper panel is the average of the deep transit events ( $\Delta F > 0.8\%$ ), and the lower panel is the average of the shallow events ( $\Delta F = 0.2 - 0.5\%$ ). Best-fit models are shown as a solid line. From Brogi et al. (2012a, Figure 3), reproduced with permission © ESO.

Other signatures attributed to tidal disruption events include a giant X-ray flare in NGC 5905 (Li et al., 2002), flares in Sgr A\* (Zubovas et al., 2012), and a hard X-ray source in NGC 6388 (Del Santo et al., 2014).

Speculatively, orbits within the tidal disruption radius might indicate the existence of ‘strange quark matter’ (Huang & Yu, 2017), with the pulsar planet PSR J1719-1438B (§4.2.2) considered a plausible candidate.

**Infall and engulfment time** Infall times for projected engulfment, or merger (§10.11.9), have also been assessed for HAT-P-23 b, an inflated hot Jupiter ( $P = 1.2$  d,  $2.1M_J$ ), with one of the shortest characteristic infall times (Equation 10.75), of  $7.5^{+2.9}_{-1.8}$  Myr, before engulfment by the star (Bakos et al., 2011a), and Kepler-91, to be swallowed in  $< 55$  Myr (Lillo-Box et al., 2014c). Other evidence for past engulfment includes stellar Li abundances (§8.4.7), and the atmospheric pollution of white dwarfs (§8.9.4).

#### 6.14.22 Disintegrating planets and dusty tails

Continued tidal decay will eventually lead to tidal disruption. The disintegration of highly irradiated planets would release large amounts of gas and dust into an exospheric tail. Disintegrating planets may also result from massive impact events.

For a transiting planet with a dusty tail, the extinction by dust removes more light from the beam than is

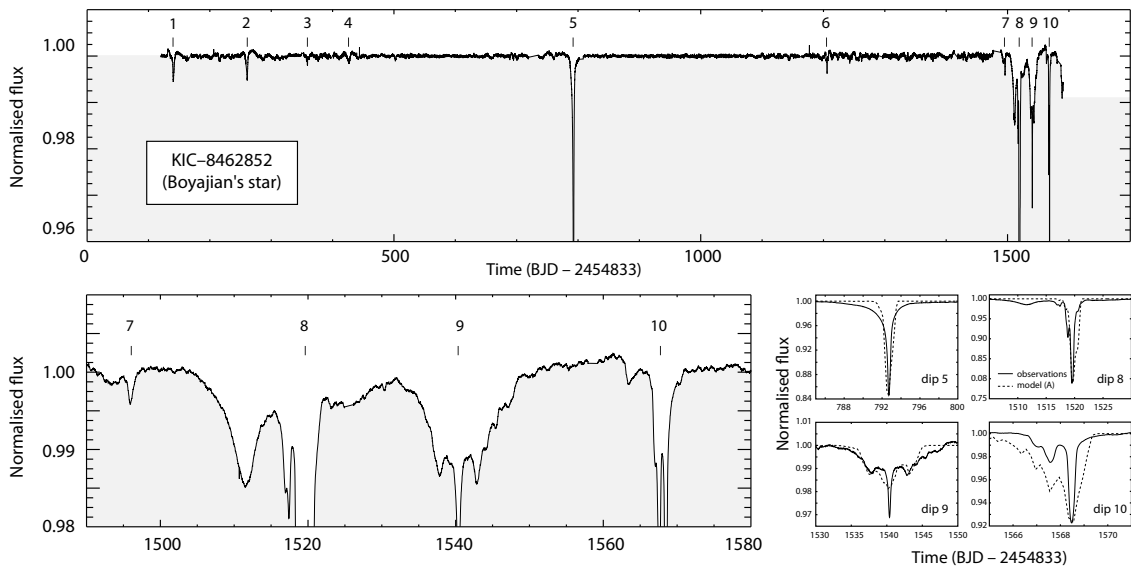


Figure 6.55: Flux time series for KIC-8462852 showing (top) the 4-yr Kepler observations (with 10 indicated dips); and (bottom left) the 90-d interval covering dips 7–10. The unusual light curve has been variously considered as explicable in terms of exocomets, consistent with a ‘swarm of megastructures’, and ‘inconsistent with any known stellar phenomenon’. From Boyajian et al. (2016, Figure 1), © Oxford University Press. Bottom right: a model comprising four co-orbiting bodies enshrouded in dust is compatible with the main features of dips 5, 8, 9, 10. From Neslušan & Budaj (2017, Figure 5), reproduced with permission © ESO.

scattered into it. Thus, the forward scattering component of the light is best seen either just prior to ingress, or just after egress, but with reduced amplitude over the larger peak that is obscured by the transit. This picture suggests that it should be equally productive to search for positive-going peaks in the flux from non-transiting exoplanets with dusty tails (DeVore et al., 2016).

**Candidates** A number of disintegrating candidates have been discovered from their unusual light curves, sequentially:

*Kepler-1520*: The first (presumed) disintegrating planet was identified orbiting the 16 mag Kepler-1520 (KIC-12557548; Rappaport et al., 2012). The star exhibits transit-like features every 15.7 h that vary in depth between 0.2–1.2% (Figure 6.54). Rappaport et al. (2012) explained these as a disintegrating rocky planet with a trailing cloud of dust of varying optical depth, created and constantly replenished by thermal surface erosion. Further observations and analyses include estimates of mass-loss rates, scattering geometry, and chemical dust composition (Brogi et al., 2012a; Kawahara et al., 2013; Perez-Becker & Chiang, 2013; Budaj, 2013, 2014; van Werkhoven et al., 2014a; Croll et al., 2014; Garai et al., 2014; van Lieshout et al., 2014; Bochinski et al., 2015; Croll et al., 2015b; van Lieshout et al., 2016).

Since the estimated mass-loss rates can only last for a few per cent of the planet’s life, Perez-Becker & Chiang (2013) estimated that for every such object, there should be 10–100 close-in quiescent progenitors with  $P < 1$  d whose hard-surface transits could be detectable by Kepler.

*KOI-2700*: Kepler candidate KOI-2700 b (KIC-8639908), with  $P = 21.8$  h, also shows a distinctly asymmetric transit profile, likely indicative of the emission of dusty effluents (Rappaport et al., 2014; van Lieshout et al., 2014; Garai, 2018). The transit egress can be followed for 25% of the orbital period and, if in-

terpreted as extinction from a dusty comet-like tail, indicates a lifetime for the dust grains of more than a day.

*WD 1145+017*: Transit events associated with this white dwarf also show a sharp ingress and slow egress, also interpreted as a cometary tail trailing the transiting object (Vanderburg et al., 2015a). It is described further in Section 8.9.4.

*K2-22*: The planet is in an ultrashort 9.1-h orbit about an M star (Sanchis-Ojeda et al., 2015a). Evidence for a dust tail includes erratically and highly variable transit depths ranging from 0.14–1.3% in both the Kepler K2 data and in follow-up ground-based observations, while the folded light curve exhibits a post-egress ‘bump’ and a less significant but plausible pre-ingress ‘bump’ that are not found in conventional hard-body transits.

*KIC-8462852* or *Boyajian’s star*: this is a Kepler discovery by the Planet Hunters project (§6.12.3) on the basis of its unusual light-curve (Boyajian et al., 2016). The discovery paper (subtitled ‘Where’s the Flux’, WTF) drew attention to pronounced dimming by up to 20%, lasting between 5–80 d, and with an irregular cadence and unusual profile (Figure 6.55a). Considerable speculation accompanied the unusual light curve, with interpretations ranging from occulting clouds of exocomets, to a ‘swarm of megastructures’, and suggested as an outstanding SETI target, by Wright et al. (2016b), and subsequently monitored as such at both radio (Harp et al., 2016a) and optical (Abeysekara et al., 2016; Schuetz et al., 2016) wavelengths.

It has since been the subject of further multi-wavelength monitoring, with continued speculation on the bodies responsible (Lisse et al., 2015; Bodman & Quillen, 2016; Montet & Simon, 2016; Schaefer, 2016; Hippke et al., 2016; Thompson et al., 2016; Makarov & Goldin, 2016a; Hippke & Angerhausen, 2016; Hippke et al., 2017; Ballesteros et al., 2018; Wyatt et al., 2018).

Other scenarios were attributed to episodic occultation by a circumstellar dust clump perhaps produced by catastrophic

collision in the system's asteroid belt, or associated with a population of dust-enshrouded planetesimals, or produced by the episodic breakout of a family of comets (Lisse et al., 2015; Marengo et al., 2015; Bodman & Quillen, 2016; Boyajian et al., 2016). Neslušan & Budaj (2017) modeled the data as four co-orbiting objects enshrouded in dust clouds, presumably the result of a break-up or impact event, and reproducing the main features observed in the light curve (Figure 6.55b).

The various possibilities have been classified as originating from structure in the interstellar medium, an intervening object with a large disk, a cloud in the outer solar system, natural and artificial material orbiting the star, and variations in the star itself (Wright & Sigurdsson, 2016; Wright, 2018). Other studies are summarised in Appendix D.

### 6.14.23 Artificial bodies and other civilisations

Transits and phase curves may contain other, more speculative, evidence of advanced civilisations (e.g. Forgan, 2013; Korpela et al., 2015), considered explicitly for Boyajian's star (§6.14.22) by Wright et al. (2016b).

**Examples** Future telescopes, on ground and in space, might be able to detect the specific phase modulation due to (strong) artificial illumination on the night-side of planets as they orbit their host stars (Loeb & Turner, 2012).

Starshades placed near Earth's inner Lagrange point (L1) have been proposed as a geoengineering solution to anthropogenic climate change (e.g. Early, 1989; Angel, 2006). Advanced versions could modulate incident irradiation over Gyr. Of order planet size, and placed at a mass-minimising distance of  $1.6\Delta(\text{Earth-L1})$ , mutual occultations during planet transits would produce a characteristic maximum at mid-transit (Gaidos, 2017b). Similarly, geoengineering through stratospheric or Lagrange-located aerosols, as proposed for Earth (e.g. Struck, 2007; Rasch et al., 2008; Bewick et al., 2012; Dykema et al., 2016), would leave their own spectral markers.

In the context of possible SETI/METI markers and search strategies (§11.8.6), Kipping & Teachey (2016) suggested that the time of transit provides a clear window in which observers may expect to communicate. They considered that a civilisation may 'cloak' their presence through controlled laser emission, or deliberately broadcast their existence by distorting their transit to an artificial shape, which would serve both as a SETI beacon, and as a medium for data transmission.

### 6.14.24 Transits across white dwarfs

The potentially very large transit depths expected from the (geometrically less-favourable) transits of a planet orbiting a white dwarf have been predicted (§6.3.4), but have not yet been observed.

An unsuccessful search in 194 white dwarfs in the WASP survey was reported by Faedi et al. (2011b). An unsuccessful search for transits in 1700 white dwarfs in the Pan-STARRS1 medium-deep fields suggests that gas giants ( $R_p \gtrsim 2R_\oplus$ ) orbiting just outside the Roche radius are rare, occurring around less than 0.5% of white dwarfs (Fulton et al., 2014). A search for transiting rocky planets around ultraviolet-bright white dwarfs was made in archival HST-COS data, placing limits down to sub-lunar radii (Sandhaus et al., 2016).

A systematic search of 1148 white dwarfs observed by K2 (van Sluijs & Van Eylen, 2018) gave various stringent constraints, for  $P < 40$  d, on hot Jupiters (<1.5%), habitable zone Earth-like planets (<28%), and disintegrating short-period planets (<12%).

**Transits of white dwarfs** In contrast to planets transiting a host white dwarf, three examples of a hot white dwarf transiting (and eclipsing) a main sequence host star have been discovered by Kepler. In these cases, the more compact, less luminous object is hotter than its stellar host, and the relative depths of the primary and secondary eclipses are consequently inverted compared to the situation for transiting exoplanets (e.g. Carter et al., 2011b, their Figure 2). The systems also show ellipsoidal light variations and Doppler beaming (§6.15.3).

The Kepler discoveries are KOI-74 (Rowe et al., 2010), KOI-81 (van Kerkwijk et al., 2010), and, with significantly larger transit and eclipse depths (0.7% and 2% respectively) KIC-10657664 (Carter et al., 2011b). Doppler beaming for KOI-74 is sufficiently large that it could be used to infer a radial velocity amplitude accurate to  $1 \text{ km s}^{-1}$ , and (the authors suggest) the first time that a radial-velocity curve has been measured photometrically (van Kerkwijk et al., 2010).

## 6.15 Orbital phase curves

Transits and secondary eclipses provide important atmospheric diagnostics for transiting planets (§6.24). Outside of the transit and eclipse phases, an orbiting planet may also reveal its presence by the modulation of reflected star light as the planet orbits its host star (Figure 6.26). Such a *phase curve*, describing the brightness variations as a function of the planet's phase angle along the orbit, depends on parameters such as the planet's orbit, its geometry relative to the observer, its oblateness, the scattering properties of its surface or atmosphere, and the presence and geometry of rings.

At optical wavelengths, the phase curve is typically dominated by reflected light from the planet, while the planet's thermal emission may contribute in the infrared. The presence of reflected light is implicit in the existence of a secondary eclipse, at least at optical wavelengths where starlight scattered off the planet's atmosphere dominates over thermal emission.

Such an orbital-modulated reflected light component would be expected, in principle, even in the absence of transits, and for all but face-on orbits.

**Resolved imaging versus integrated light** There are two approaches to the detection of such phase variations. With sufficient angular resolution, direct imaging can (in principle) separately resolve the planet and star, and the projected planetary orbit can be tracked simultaneously with the measurement of the planet's phases in reflected light.

To be detectable, such planets must be at orbital distances large enough to be resolved from their parent star, but close enough that the reflected brightness can be detected. Consequently, the first planets that are being detected.

tected directly in this way are giants orbiting relatively nearby stars (at 10–20 pc), and with intermediate semi-major axes of 1–5 au.

The second approach, considered here, exploits precise, integrated photometry, searching for temporal variations in the combined light from the (dominating) host star and planet. Since the two objects need not be spatially resolved, relatively distant planetary systems and planets at small physical orbital radii can be studied.

**Higher-order effects** The theoretical formulation and observational constraints have evolved since the first attempts to detect reflected light from an orbiting planet. The expected signatures are now frequently formulated and constrained in the context of a full modeling of the out-of-transit orbital photometry or phase curve. In this formulation, not only the reflected light component, but all other orbit-modulated contributions, are taken together. When discernible, these higher-order effects, considered further in the following sections, are dominated by *Doppler beaming* and *ellipsoidal variations*.

### 6.15.1 Reflected light

**Heritage from eclipsing binaries** Before the study of exoplanet phase curves, the phenomenon of reflection modulation was already well-known in the field of eclipsing binaries, where the flux of each component also illuminates the facing half of its companion (e.g. Wilson, 1990; Maxted et al., 2002; Harrison et al., 2003; For et al., 2010; Reed et al., 2010).

Bromley (1992) already proposed to use reflected light during bright stellar flares, noting that *possible planetary configurations that may be probed by this method are limited to Jupiter-size objects in tight orbits about the parent star*. Other considerations (Charbonneau et al., 1998; Seager & Sasselov, 1998; Seager et al., 2000) led to the first direct searches.

**Theoretical formulation** The theoretical framework has been developed and presented by various authors (Collier Cameron et al., 1999, 2002; Leigh et al., 2003a; Rodler et al., 2010; Kane & Gelino, 2010; Budaj, 2011; Cowan et al., 2013), with the following as given by Kane & Gelino (2010).

With respect to the top-down view of an elliptical planetary orbit shown in Figure 6.56a, the *phase angle*  $\alpha$  is described by

$$\cos \alpha = \sin(\omega + \nu) \sin i, \quad (6.88)$$

where  $\omega$  is the argument of pericentre and  $\nu$  is the true anomaly (§2.1.1). By convention, the phase angle is defined to be  $\alpha = 0^\circ$  when the planet is at superior conjunction, corresponding to  $\omega + \nu = 270^\circ$ .

The flux at wavelength  $\lambda$  incident on the planet is

$$F_i(\lambda) = \frac{L_\star(\lambda)}{4\pi r^2}, \quad (6.89)$$

where  $L_\star$  is the luminosity of the star and  $r$  is the star–planet separation. This separation is given by

$$r = \frac{a(1 - e^2)}{1 + e \cos \nu}. \quad (6.90)$$

The geometric albedo of a planet is defined at  $\alpha = 0^\circ$  as

$$p(\lambda) = \frac{F_r(0, \lambda)}{F_i(\lambda)}, \quad (6.91)$$

where  $F_r$  is the reflected light from the planet. The planetary flux received at Earth is then

$$f_p(\alpha, \lambda) = p(\lambda) g(\alpha, \lambda) F_i(\lambda) \frac{R_p^2}{r^2}, \quad (6.92)$$

where the *phase function*,  $g(\alpha, \lambda)$ , describes the brightness of a reflecting body as a function of its phase angle. The flux ratio of the planet to the host star is then

$$\epsilon(\alpha, \lambda) \equiv \frac{f_p(\alpha, \lambda)}{f_\star(\lambda)} = p(\lambda) g(\alpha, \lambda) \frac{R_p^2}{r^2}. \quad (6.93)$$

The wavelength dependence of the geometric albedo and phase function follow from the scattering properties as a function of atmospheric composition.

Since the relative amplitude of the reflected light decreases with the square of the planet–star distance, the proximity of hot Jupiters to their host stars makes them optimum targets for reflected-light searches. There is no modulation for face-on systems,  $i = 0^\circ$ . For a circular orbit, only the phase function is time dependent.

**Geometric albedo** The geometric albedo  $p(\lambda)$  is the ratio of brightness at zero phase (i.e., seen from the star) to that of a fully reflecting, diffusively scattering (Lambert) flat disk with the same cross section. For a Lambert sphere,  $p(\lambda) = 2/3$ .

Atmospheric models demonstrate that the geometric albedo of giant planets depends on the semi-major axis of the orbit (e.g. Sudarsky et al., 2000, 2005; Cahoy et al., 2010).

Compared with Jupiter’s visual geometric albedo of  $\sim 0.5$ , the strong irradiation of the atmospheres of giant planets in short-period orbits results in the removal of reflective condensates from the upper atmospheres, and thus a significant lowering of the geometric albedo. For example, the absence of detected phase variations for HD 209458 b observed with MOST (Rowe et al., 2008) gave an upper limit of  $p < 0.08$ . Observations of HAT-P-7 b using Kepler revealed phase variations from which Welsh et al. (2010) deduced  $p \sim 0.18$ , while Cowan & Agol (2011b) suggested that others may have a much larger albedo, of up to 0.5.

Kane & Gelino (2010) derived a model which approximates the geometric albedo of giant planets as a function of star–planet separation

$$p = \frac{(e^{r-1} - e^{-(r-1)})}{5(e^{r-1} + e^{-(r-1)})} + \frac{3}{10}. \quad (6.94)$$

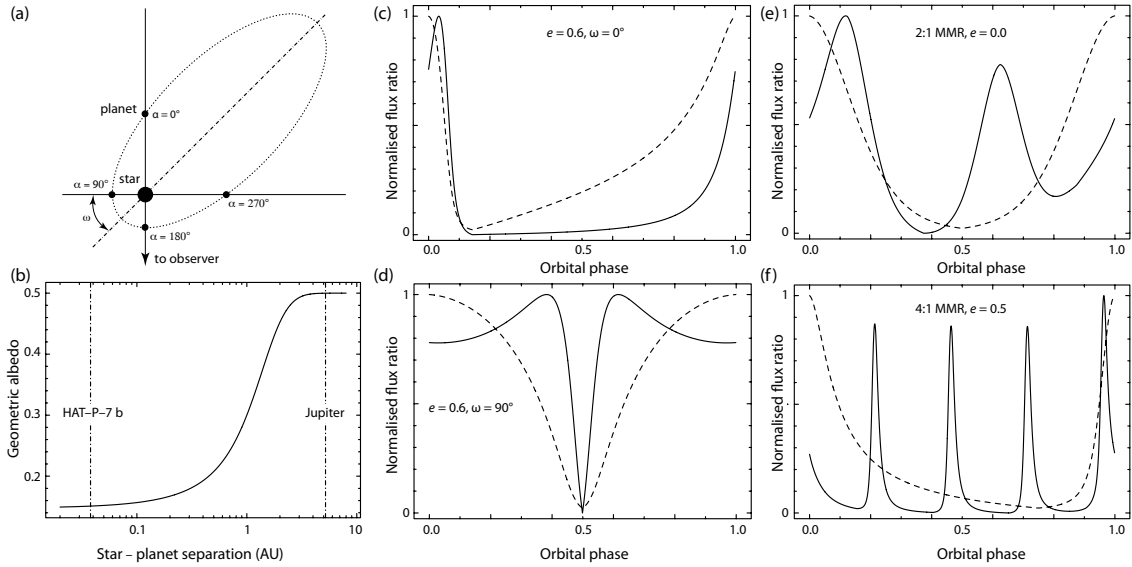


Figure 6.56: Theoretical photometric phase variations throughout a planetary orbit: (a) eccentric orbit schematic, with phase angles corresponding to full ( $\alpha = 0^\circ$ ), first quarter ( $90^\circ$ ), new ( $180^\circ$ ), and third quarter ( $270^\circ$ ) phases; (b) geometric albedo for giant planets at 550 nm, with the semi-major axes of HAT-P-7 b and Jupiter shown for reference; (c–d) normalised flux ratio (solid line) and phase function (dashed line) for  $e = 0.6$  and  $\omega = 0^\circ$  (top), and  $e = 0.6$  and  $\omega = 90^\circ$  (bottom); (e–f) normalised flux ratio (solid line), and phase function of the outer planet (dashed line), for a 2-planet system in 2:1 resonance with  $e = 0.0$  (top), and 4:1 resonance with  $e = 0.5$  (bottom). From Kane & Gelino (2010, Figures 1–4), by permission of IOP Publishing/AAS.

This (hyperbolic tangent) function is shown in Figure 6.56b. It represents the rapid rise in optical albedo between 0.2 and 1 au described by Sudarsky et al. (2005), as well as the continued rise beyond 2 au as H<sub>2</sub>O clouds begin to form.

**Phase function** The phase function of a Lambert sphere assumes that the atmosphere scatters isotropically over  $2\pi$  sr. It is given by (Sobolev, 1975; Charbonneau et al., 1999)

$$g(\alpha, \lambda) = \frac{\sin \alpha + (\pi - \alpha) \cos \alpha}{\pi}, \quad (6.95)$$

having a value between 0 and 1.  $\alpha$  is related to the true anomaly and the orbit inclination through Equation 6.88. For a circular orbit, the phase function applied to the flux ratio relation (Equation 6.93) results in both a phase function and flux ratio which are maximum at  $\alpha = 0$ . The time-dependent variation of the phase function is related to the orbital geometry through the solution of Kepler's equation (Equation 2.10).

Within the solar system, the majority of bodies are strongly non-Lambertian, tending to reflect light straight back to its source, rather than scattering it diffusively. Thus for Jupiter, Saturn, Uranus, and Neptune,  $p(480 \text{ nm}) = 0.46, 0.39, 0.60,$  and  $0.58$ , respectively (Karkoschka, 1994). Phase variation models for Jupiter and Saturn (and its rings) have been constructed for varying orbital and viewing parameters, using scattering

measured by Pioneer and Voyager at  $0.6\text{--}0.7 \mu\text{m}$  (Dyudina et al., 2005). Others have been constructed for Mercury, Venus, and Mars (Mallama, 2009).

Various authors (Collier Cameron et al., 2002; Kane & Gelino, 2010; Rodler et al., 2010) therefore used, instead, the empirical phase function of Hilton (see Seidelmann, 1992), which was based on observations of Jupiter and Venus, incorporates substantially more back-scattering due to cloud-cover, and contains a corresponding correction to the planet's visual magnitude

$$g(\alpha) = 10^{-0.4\Delta m(\alpha)}, \quad (6.96)$$

where

$$\Delta m(\alpha) = 0.09 \left( \frac{\alpha}{100^\circ} \right) + 2.39 \left( \frac{\alpha}{100^\circ} \right)^2 - 0.65 \left( \frac{\alpha}{100^\circ} \right)^3. \quad (6.97)$$

Figure 6.56c–d show example phase functions and normalised flux ratios for two combinations of eccentricities and orbital orientations. The maximum flux ratio does not necessarily occur at zero phase angle for a non-circular orbit, because of the changing orbital distance (Sudarsky et al., 2005).

Departures from a sinusoidal phase curve could indicate non-isotropic scattering, for example, due to small atmospheric particles (e.g. Seager et al., 2000). Asymmetries or phase shifts may arise from lateral variations in cloud cover, or temperature, arising from atmospheric circulation (e.g. Showman & Guillot, 2002).

**Orbit inclination** Various system parameters depend on the orbit inclination,  $i$ . Accordingly, for any assumed albedo, the amplitude of the phase variation could (in principle) be used to estimate  $i$ , and therefore (for example) constrain the planet mass derived from radial velocity data (Charbonneau et al., 1999; Cowan et al., 2013). At first and third quarter ( $\alpha = 90^\circ$  and  $\alpha = 270^\circ$ ), the flux ratio is independent of  $i$  (Figure 6.56a). The phase function is reduced in amplitude for orbits inclined to the line-of-sight, with time-dependent signatures completely suppressed for face-on orbits,  $i = 0^\circ$ .

**Eccentric orbits in non-transiting systems** Even if they do not transit, planets in highly eccentric orbits are likely to produce relatively high phase amplitudes, at least during the period of pericentric passage. Highly-eccentric non-transiting systems (e.g. HAT-P-13, HD 37605, and HD 82943) may therefore provide the best prospects for exploring the atmospheric properties of longer-period planets (Kane & Gelino, 2010).

The same phenomenon offers the opportunity of discovering non-transiting hot Jupiters interior to the orbits of known transiting systems, which may then also correlate with astrometrically-induced transit timing variations for the exterior transiting planet (§6.20.2, case A). Millholland et al. (2016) searched the Kepler candidates, and identified a potential non-transiting hot Jupiter in the KOI-1822 system, showing sinusoidal light variations (their Figure 4) as well as significant transit timing variations (Holczer et al., 2016). Some 60 non-transiting hot Jupiter candidates were identified in the follow-up study by Millholland & Laughlin (2017b).

**Effects of polarisation** Ignoring polarisation (§6.17) will affect the interpretation of reflected light curves, especially for elliptical orbits, or if the planet is oblate (Stam & Hovenier, 2005; Sengupta & Maiti, 2006).

**Simplified form** A first-order approximation to the reflection modulation assumes that the reflected light, along with any thermal emission from the planet day-side, are modulated with the same phase (e.g. Snellen et al., 2009a; Mazeh & Faigler, 2010). The amplitude of the modulation of the reflected light alone is

$$A_{\text{refl}} \sim p \left( \frac{R_p}{r} \right)^2. \quad (6.98)$$

Including both reflected light and thermal emission

$$A_{\text{refl}} \sim \alpha_{\text{refl}} 0.1 \left( \frac{R_p}{a} \right)^2, \quad (6.99)$$

where  $\alpha_{\text{refl}}$  is of order unity.

**Early results: non-transiting planets** In the optical, detection of reflected light from non-transiting planets is particularly challenging because of the faintness of the

signal, of the order of  $10^{-4}$  in the most favourable cases. Investigations were initially restricted to hot Jupiters.

Charbonneau et al. (1999) selected  $\tau$  Boo for study, with  $P = 3.3$  d and  $a = 0.046$  au. Although the star–planet separation is at most 3 mas, the reflected light component is  $L_p/L_\star \sim 10^{-4}$ , some  $10^4 - 10^5$  times higher than for Jupiter. From Keck–HIRES observations over three nights, no evidence for a highly reflective planet was found, yielding a geometric albedo  $p \lesssim 0.3$ .

Reports of a detected modulation at the orbital period (Collier Cameron et al., 1999), and a weak  $\text{CH}_4$  signature in the infrared spectrum (Wiedemann et al., 2001), were followed by more stringent limits from 75 h of échelle spectroscopy at the 4.2-m WHT telescope over 17 nights which revised the claim (Leigh et al., 2003b). Searches giving only upper limits were also conducted for the  $P = 4.6$ -d  $\nu$  And (Collier Cameron et al., 2002), and the 3.5-d orbital period HD 75289 (Leigh et al., 2003c; Rodler et al., 2008).

Success, in the mid-infrared at least, came with observations of  $\nu$  And at  $24 \mu\text{m}$  with Spitzer (Harrington et al., 2006). They measured the flux at five epochs over the 4.6-d period, achieving a S/N of 6300 at each. Their observations allowed them to determine the planet/star flux ratio of  $(2.9 \pm 0.7) \times 10^{-3}$ . Their detection of such a modulation also demonstrated that there is a significant illumination difference between the planet's day- and night-sides.

A subsequent determination, also from  $24 \mu\text{m}$  Spitzer–MIPS data (Crossfield et al., 2010), is shown in Figure 6.57. A large phase offset of  $\sim 80^\circ$  with respect to the radial velocity curve suggests a planet ‘hot spot’ advected almost to the planet's day–night terminator (§6.24). They determined a ‘hot side’ temperature of  $\sim 1800$  K, implying a hemisphere-averaged temperature contrast of  $\sim 900$  K, and an orbital inclination  $i \gtrsim 28^\circ$ .

Infrared phase variations were also detected with Spitzer–IRAC for HD 179949 b (Cowan et al., 2007).

Attempts to measure reflected light from  $\nu$  And using CHARA–MIRC closure phase (§6.9.3) are described by Zhao et al. (2008). Unsuccessful or unconfirmed searches were also reported for HD 75289A b (Rodler et al., 2008),  $\tau$  Boo b (Charbonneau et al., 1999; Rodler et al., 2010, 2013b), HD 46375 b (Gaulme et al., 2010b), and HD 217107 (Cubillos et al., 2011).

**Early results: transiting planets** In the optical, the first full phase light curves were reported for the gas giant CoRoT-1 b, with an amplitude 130 ppm (Figure 6.96) by Snellen et al. (2009a). Subsequently, full optical phase curves were provided by Kepler, firstly for HAT-P-7 b (Welsh et al., 2010), and subsequently for the transiting terrestrial mass planet Kepler-10 b (Batalha et al., 2011; Fogtman-Schulz et al., 2014). In the infrared, using Spitzer, phase variations were first detected for HD 189733 b (Knutson et al., 2009c) and HD 149026 b



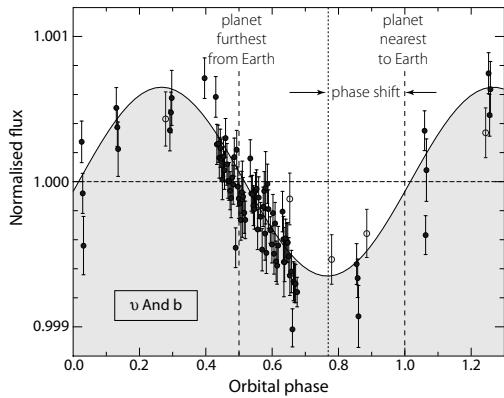


Figure 6.57: *v And b*, observed at  $24\ \mu\text{m}$  with *Spitzer*, showing reflected light modulated at the 4.6-d orbital period. The best-fit sinusoid (solid curve) exhibits a phase offset of  $\sim 80^\circ$ , indicating a planet ‘hot spot’ advected almost to the planet’s day–night terminator. Circles represent earlier *Spitzer* data from Harrington et al. (2006). From Crossfield et al. (2010, Figure 3), by permission of IOP Publishing/AAS.

(Knutson et al., 2009c). These full orbital phase curves, and associated inferences on atmospheric effects, are considered further in Section 11.6.3.

Reflected light from a (possibly transiting) planet has also been detected in the cross-correlation function in high-resolution (radial velocity) spectroscopy, both in the infrared (starting with  $\tau$  Boo b observed with VLT–CRIRES) and in the optical (51 Peg b observed with HARPS). These are detailed further in Section 2.5.4.

**Simulations for Kepler** Brown (2009b) parameterised the photometric orbit as a Keplerian entity, i.e. governed by the dynamical motion of two gravitationally-interacting bodies (and therefore analogous to the classical treatment of both radial velocity and astrometric orbit determinations). The six photometric Keplerian parameters are  $a$ ,  $e$ ,  $i$ , the mean anomaly, the argument of pericentre, and an effective planet radius.

Simulation of the Kepler satellite observations, assuming a precision of  $2 \times 10^{-5}$  over three years, showed that detections and orbital solutions might be possible for many of the 100–760 hot Jupiters that it might discover (Jenkins & Doyle, 2003).

**Predictions for radial velocity discoveries** Kane & Gelino (2010) considered the orbital parameters of the 370 exoplanets known at the time, calculated the orbital phase of maximum flux ratio,  $e_{\text{max}}$  and, for optimal observations of phase variations, the time span during which the maximum change in flux ratio occurs,  $\Delta t$ . In analogy with the transit prediction window described by Kane et al. (2009), they introduced the *phase prediction window*, the time period during which a particular orbit phase could occur according to the uncertainties on the known orbital period and the time of pericentre passage.

They presented specific examples of predicted phase amplitudes and detectability for several known exoplanets, including HD 37605 (with a predicted peak flux ratio  $0.56 \times 10^{-5}$ , with the time between minimum and maximum flux ratio being 0.04 in orbital phase, or  $\sim 2.0$  d), HAT–P–13, and HD 82943. The planet with the highest eccentricity, HD 80606 b, is also the planet with the highest predicted flux ratio.

Kane & Gelino (2011a) made a similar exercise to estimate the thermal properties and albedos, and hence detectability of long-period eccentric giant planets in the infrared, due to their thermal emission. Amongst their well-suited candidates are HD 156846 b, HD 37605 b and HD 33283 b, having bright host stars, relatively high predicted flux ratios, and brief periods of large changes in the flux ratio.

Maurin et al. (2012) examined the possibility of using multi-wavelength infrared phase curves to constrain the radius, albedo, and inclination of a non-transiting planet in a 1:1 spin–orbit resonance. They found that airless planets can be distinguished from planets having a dense atmosphere, and that their radius, albedo, and inclination (and therefore mass) can be retrieved from 5–15  $\mu\text{m}$  observations with JWST–MIRI and ARIEL/EChO. The accuracy depends on stellar type, orbital distance, radius of the planet and inclination: hot and large planets on highly inclined orbit are favoured.

**Future prospects** More comprehensive measurements will be possible with future instruments such as the James Webb Space Telescope (JWST), and the ground-based E–ELT, Thirty Meter Telescope (TMT), and Giant Magellan Telescope (GMT).

### 6.15.2 Glint

The specular reflection of sunlight off the Earth’s oceans viewed at oblique angles is known as *glint*. The same effect, recognised in visible and near-infrared exoplanet phase light curves, could indicate the presence of oceans or ice (Williams & Gaidos, 2008; Robinson et al., 2010; Zuger et al., 2010; Cowan et al., 2012a; Robinson et al., 2014a; Visser & van de Bult, 2015; Kawahara, 2016).

**Models** Models of exoplanet light curves having Earth-like surfaces, seasons, and optically-thin atmospheres, show that planets partially covered by water will appear up to a factor 2 brighter near crescent phase because of efficient specular reflection of incident star light off the oceans at appropriate orientations (Williams & Gaidos, 2008; Robinson et al., 2010).

Such planets orbiting within  $30^\circ$  of edge-on will show pronounced glint over a wide range of orbit longitudes, from quadrature to crescent. Williams & Gaidos (2008) showed that  $\text{H}_2\text{O}$ -covered planets will appear darker than Lambert disks near full illumination, and that planets with a mixed land/water surface will polarise the reflected signal by up to 30–70%.

Forward scattering of radiation by clouds can also produce increases in a planet’s reflectivity as it approaches crescent

phases, while surface glint can be obscured by Rayleigh scattering and atmospheric absorption (Robinson et al., 2010).

**Earth observations** Detailed observational verification has come with the Lunar CRater Observation and Sensing Satellite (LCROSS; Colaprete et al., 2012). LCROSS observed the distant Earth on three occasions in 2009, spanning a range of phase angles, and including a rare crescent phase view (Robinson et al., 2014a). At each epoch, it acquired near- and mid-infrared full-disk images, and partial-disk spectra at 0.26–0.65  $\mu\text{m}$  and 1.17–2.48  $\mu\text{m}$ . The spectra show strong absorption due to  $\text{H}_2\text{O}$  and  $\text{O}_3$ , and strong ocean glint in the crescent phase.

Launched in 2015, the Deep Space Climate Observatory (DSCOVR) spacecraft, from L1, monitors the solar wind, coronal mass ejections, and phenomena on Earth including  $\text{O}_3$ , dust, volcanic ash, cloud height, vegetation cover and climate. The polychromatic imaging camera delivers nearly hourly observations of the entire sunlit face of Earth. Many images contain unexpected bright flashes of light over both ocean and land, shown to be specular reflections off tiny ice platelets floating nearly horizontally in the air (Marshak et al., 2017).

### 6.15.3 Beaming, ellipsoidal, and reflection effects

In addition to reflected light from the star by the planet (including heating of its atmosphere by the stellar radiation), a more complete treatment of the full orbital phase curve for short-period systems includes two other effects which may modify the photometric variability along the orbit: Doppler beaming caused by the host star's changing radial velocity, and ellipsoidal distortions resulting from tides on the star raised by the planet (e.g. Loeb & Gaudi, 2003; Zucker et al., 2007; Faigler & Mazeh, 2011; Shporer et al., 2014; Shporer, 2017).

**Collective modeling: BEER** Collective consideration of these three phase curve effects forms the basis of the BEER algorithm (Faigler & Mazeh, 2011; Shporer et al., 2011), an acronym constructed from the three effects (BEaming, Ellipsoidal distortions, and Reflection). Since beaming modulation alone cannot necessarily be distinguished from say, stellar variability, the algorithm searches for light curves showing a combination of the beaming effect with the two additional modulations.

These components are considered separately in the following sections. Meanwhile, various systems have been analysed according to these principles, some using the specific Bayesian-inference algorithmic implementation EXONEST (Placek et al., 2014; Knuth et al., 2017).

Kepler-76 was the first hot Jupiter to be detected by BEER and subsequently confirmed by radial velocity spectroscopy (Faigler et al., 2013). Eight other close-in Kepler candidates showing secondary eclipses as well as phase variations were analysed by Esteves et al. (2013), and are shown in Figure 6.107.

Others have since been identified, including Kepler-13 (Shporer et al., 2014; Placek et al., 2014); Kepler-91 (Placek et al., 2015); Kepler-7, Kepler-12, and Kepler-41 (Shporer & Hu, 2015); and the low mass Kepler-762, Kepler-1517, and KOI-554 (Lillo-Box et al., 2016c).

### 6.15.4 Doppler beaming

*Doppler beaming* (or *Doppler boosting*) describes the collective effects of the host star's changing radial velocity along the orbit (the non-relativistic effect due to non-zero spectral index is considered in §6.13.8). To first order, beaming causes a decrease of the brightness of a source receding from the observer, and *vice versa* (Rybicki & Lightman, 1986). Variations of the stellar radial velocity due to an orbiting companion therefore result in modulation of the stellar flux. The effect is of the order  $4v_r/c$ , where  $v_r$  is the radial velocity of the source.

Identified as an effect in ultracompact binary stars (Shakura & Postnov, 1987; Zucker et al., 2007), Loeb & Gaudi (2003) suggested its use to identify non-eclipsing binaries and exoplanets in the CoRoT and Kepler data. Space observations are needed because even for short-period binaries, with large radial velocity amplitudes, the beaming effect is small, of order 100–500 ppm. Beaming has since been identified in a number of non-eclipsing binaries in the CoRoT data (Tal-Or et al., 2015).

More completely, several effects contribute, all to first order in  $v_r/c$  (Jackson et al., 2012b): (1) transformation of the energy–momentum four-vector from the comoving stellar frame to that of the observer (Rybicki & Lightman, 1986, eqn 4.93); (2) reduction in apparent size of the star as it recedes (op. cit., eqn 4.95); (3) increased light travel time as the star recedes (op. cit., eqn 4.97); and (4) Doppler shifting of the stellar flux convolved with the observational (filter) bandpass.

Together, effects (1)–(3) increase the stellar flux as the star approaches the observer. The peak in emission for certain systems, such as HAT-P-7, occurs blueward of the Kepler bandpass, so the accompanying blueshift reduces the apparent flux.

The contribution from the changing light travel time leads to transit ingress advancing at a higher rate than egress by  $\sim 10^{-4} - 10^{-3}$  for hot Jupiters (Loeb, 2005).

**Beaming amplitude** For circular orbits, the beaming effect, of amplitude  $A_{\text{beam}}$ , can be modeled as (Loeb & Gaudi, 2003; Zucker et al., 2007; Esteves et al., 2013)

$$F_{\text{beam}} = A_{\text{beam}} \sin(2\pi\phi) \\ \approx \alpha_{\text{beam}} \frac{K}{c} \sin(2\pi\phi) \quad \text{for } K \ll c \text{ and } e = 0, \quad (6.100)$$

where  $\alpha_{\text{beam}}$  is the photon-weighted bandpass-integrated beaming factor, typically of order unity (e.g. Loeb & Gaudi, 2003; Bloemen et al., 2011), and  $K$  is the radial velocity semi-amplitude.

For brown dwarf or planet companions, the beaming effect is  $\sim 2$ –50 ppm, as determined for CoRoT-3 (Mazeh & Faigler, 2010), HAT-P-7 (Jackson et al., 2012b; Mislis et al., 2012), Kepler-13 (Shporer et al., 2011; Mazeh et al., 2012), and TrES-2 (Barclay et al., 2012).

**Beaming in non-planetary systems:** Unlike reflection and ellipsoidal effects, which have been recognised as observables in eclipsing binaries for some time, beaming was only observed more recently, from both space and ground. Non-exoplanet manifestations include a few Kepler white dwarf companions, including KOI-74 (van Kerkwijk et al., 2010; Carter et al., 2011b; Ehrenreich et al., 2011a), CoRoT-3 (Mazeh & Faigler, 2010), the Kepler short-period eclipsing binary KPD 1946+4340 (Bloemen et al., 2011), and various other CoRoT and Kepler systems (Faigler & Mazeh, 2011).

The identification of *non-eclipsing* binaries through detection of beaming was also considered (Loeb & Gaudi, 2003; Zucker et al., 2007), assuming that other effects such as variability can be excluded (e.g. Aigrain et al., 2004). Faigler et al. (2012) subsequently reported radial velocity confirmation of seven new non-eclipsing short-period binary systems in the Kepler field, with companion masses in the range  $0.07 - 0.4M_{\odot}$ , discovered using the combined beaming, ellipsoidal, and reflection effects.

Observations from the ground include the candidate Type Ia supernova progenitor KPD 1930+2752 (Maxted et al., 2000), a detached double white dwarf binary (Shporer et al., 2010a), and the fourth hot white dwarf companion KOI-1224 (Breton et al., 2012).

### 6.15.5 Ellipsoidal variations

**Ellipsoidal variable stars** Ellipsoidal variables are close binaries whose components are distorted by their mutual gravitation, but whose orbit inclinations are too small to create eclipses (Morris & Naftilan, 1993; Morris, 1985; Wilson, 1990; Orosz & Hauschildt, 2000; Quintana et al., 2013). Such stars are not exactly ellipsoidal in shape but, rather, fill their Roche equipotential surfaces. Resulting light curves, due to the changing projected areas and surface brightnesses of the distorted stars, typically have amplitudes of only a few per cent.

The ellipsoidal effect for close binaries can be estimated from the analytical approximation of Morris & Naftilan (1993), who used the Kopal (1959) expansion of the periodic variation into discrete Fourier series with terms that depend on  $R_{\star}/a$  (see also Pfahl et al., 2008). For small  $R_{\star}/a$ , the leading term has semi-amplitude

$$A_{\text{ellip}} \simeq \alpha_{\text{ellip}} \frac{M_{\text{p}}}{M_{\star}} \left( \frac{R_{\star}}{a} \right)^3, \quad (6.101)$$

where

$$\alpha_{\text{ellip}} = 0.15 \frac{(15 + u)(1 + g)}{3 - u} \quad (6.102)$$

is of order unity. Here,  $g$  is the stellar gravity darkening coefficient, and  $u$  is the limb-darkening coefficient.

**Star-planet systems** The assumption of sphericity for transit modeling also breaks down in the case of close-orbiting planets. Tidal distortion of the star by the planet results in *ellipsoidal variations*, a periodic flux modulation (twice per orbit) due to changes of the star's visible surface area as the stellar tide, created by the planet, rotates in and out of view (Figure 6.58). The resulting light

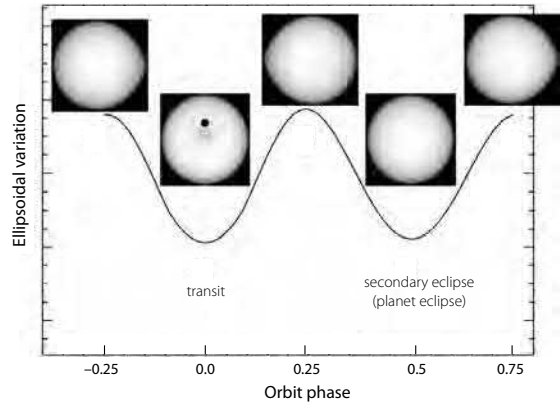


Figure 6.58: Schematic of ellipsoidal variations (arbitrary units) versus orbit phase. Phase 0 shows the planet during transit (transit signature not included), phases  $-0.25$  and  $0.25$  at quadrature, and phase  $0.75$  at secondary eclipse. From Jackson et al. (2012b, Figure 2), by permission of IOP Publishing/AAS.

curve can be modeled following the same principles developed for binary stars (Wittenmyer et al., 2005; Mislis et al., 2012; Jackson et al., 2012b).

The presence of ellipsoidal variations in exoplanet systems was anticipated by Loeb & Gaudi (2003) and Drake (2003). Pfahl et al. (2008) presented a detailed theoretical investigation, and estimated that the effect could be detected in some 100 Kepler targets.

**Observations** Ellipsoidal variations were first seen in the bright Kepler-field system HAT-P-7 b, in which a transiting hot Jupiter of  $1.7M_{\text{J}}$  orbits an F6 star with  $a = 4R_{\star}$ . HAT-P-7 was observed throughout the Kepler mission at one-minute cadence. Using only the first 10 d of observations, Borucki et al. (2009) detected the secondary eclipse at optical wavelengths, finding an eclipse depth of  $130 \pm 11$  ppm, as well as orbital phase variations.

Welsh et al. (2010) determined that these phase variations were dominated by perturbations due to ellipsoidal variations in the shape of the host star caused by the gravity of the planet, resulting in brightening of the system on either side of the secondary eclipse with an amplitude of  $\sim 60$  ppm (Figure 6.59). The ellipsoidal variations were further studied, using Q1-Q2 Kepler data, by Mislis et al. (2012) and Jackson et al. (2012b).

Detailed calculations and functional forms depend on the specific models. For example, to model the Kepler light curve of HAT-P-7, Welsh et al. (2010) integrated the light originating from the individual surface elements of the rotating star, which is slightly deformed by the tidal force induced by its small companion (e.g. Orosz & Hauschildt, 2000). Other predictions of the ellipsoidal variations for HAT-P-7, and the possibility of deriving the planet mass, were noted by Mislis et al. (2012).

Detecting the beaming effect together with the ellipsoidal and reflection periodic variations, with the ex-

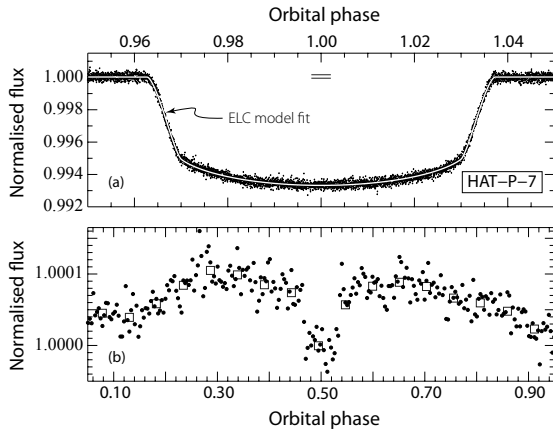


Figure 6.59: The Kepler light curve of HAT-P-7: (a) phase-folded light curve across the transit at 1 min cadence, with the fit from the ELC model code of Orosz & Hauschildt (2000) superimposed (white line); (b) the light curve over the full orbital period averaged in 5 min (filled circles) and 75 min (open squares) bins. The double-hump profile is due to the ellipsoidal variations of the star plus reflected light from the planet. The vertical extent of the lower panel is indicated by the central horizontal lines in (a). From Welsh et al. (2010, Figure 1), by permission of IOP Publishing/AAS.

pected relative amplitudes and phases, can also indicate the presence of a *non-eclipsing* companion.

The collective beaming, ellipsoidal, and reflection effects in the Kepler observations of HAT-P-7 by Jackson et al. (2012b) are illustrated in Figure 6.60.

Ellipsoidal variations in WASP-12 b, detected at 3.6 and 4.5  $\mu\text{m}$  with Spitzer, suggest a near 3:2 ratio between the planet's major and minor axes (Cowan et al., 2012b).

**Modeling** In the absence of tidal lag, the star's visible surface area and ellipsoidal variations are at a maximum when the direction of the tidal bulge is perpendicular to the observer's line-of-sight, and at minimum during the transit and secondary eclipse. Morris (1985, equations 1–3) then describe the ellipsoidal light curve as a linear combination of the first three cosine harmonics of the planet's period. As used by Esteves et al. (2013)

$$F_e = -A_e [\cos(2\pi \cdot 2\phi) + f_1 \cos(2\pi\phi) + f_2 \cos(2\pi \cdot 3\phi)] ,$$

where  $A_e$  is the amplitude of the dominant harmonic

$$A_e = \alpha_2 \frac{M_p}{M_\star} \left( \frac{a}{R_\star} \right)^{-3} \sin^2 i , \quad (6.103)$$

$f_1$  and  $f_2$  are defined by

$$f_1 = 3\alpha_1 \left( \frac{a}{R_\star} \right)^{-1} \frac{5 \sin^2 i - 4}{\sin i} \quad (6.104)$$

$$f_2 = 5\alpha_1 \left( \frac{a}{R_\star} \right)^{-1} \sin i , \quad (6.105)$$

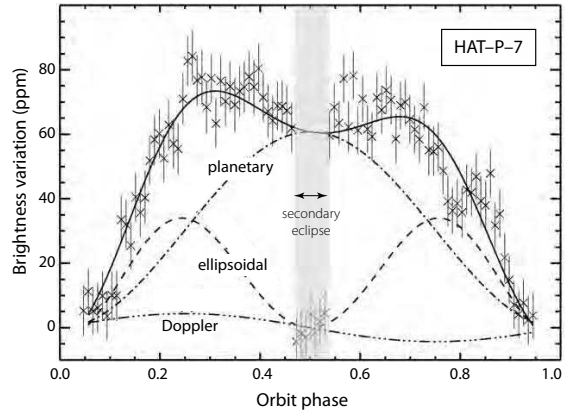


Figure 6.60: Illustration of the Doppler beaming, ellipsoidal, and reflection effects in the Kepler observations of HAT-P-7. Observations from Q0-2 are co-phased and binned to 30 min. Curves show the overall best-fit model (solid line), as well as for the individual components due to Doppler beaming, ellipsoidal, and reflection effects. The eclipse, not fit by the model, is shown in grey. Residuals have  $\sigma \sim 8$  ppm, and are nearly normally distributed. From Jackson et al. (2012b, Figure 3), by permission of IOP Publishing/AAS.

and the constants  $\alpha_1$  and  $\alpha_2$  are given by

$$\alpha_1 = \frac{25u}{24(15+u)} \left( \frac{y+2}{y+1} \right) \quad (6.106)$$

$$\alpha_2 = \frac{3(15+u)}{20(3-u)} (y+1) , \quad (6.107)$$

where  $u$  and  $y$  are linear limb darkening (§6.14.1) and gravity darkening parameters (§6.14.3), respectively.

The mass of the planet,  $M_p$ , is the only free parameter in the fit of the ellipsoidal variations.

**O'Connell effect** Related photometric light curve asymmetries are observed in some close eclipsing binaries (e.g. Sri-ram et al., 2017), although not yet in exoplanet systems. The *O'Connell effect* does not necessarily appear near pericentre, when tidal effects and increased mutual radiation cause the most prominent luminosity increase (O'Connell, 1951), and has been variously attributed to an asymmetric distribution of star spots, one-way gas streams between the binary components, or to a flow of circumstellar matter, asymmetrically deflected due to Coriolis forces (Wilsey & Beaky, 2009).

### 6.15.6 Collective modeling

For the modeling of all phase curve effects together, transit light curve fitting provides estimates of  $b$ ,  $a/R_\star$ ,  $R_p/R_\star$ , and the linear and quadratic limb-darkening coefficients. For cases where the observed secondary eclipse is centred on  $\phi = 0.5$ , the orbit can be considered as having  $e = 0$ , and the secondary eclipse similarly modeled according to Mandel & Agol (2002).

The out-of-transit phase curve can then be modeled as (Esteves et al., 2013)

$$\frac{\Delta F}{F} = f_0 + F_{\text{ecl}}(\phi) + F_p(\phi) + F_{\text{beam}}(\phi) + F_{\text{ellip}}(\phi) , \quad (6.108)$$

representing an arbitrary zero point ( $f_0$ ), the secondary eclipse ( $F_{\text{ecl}}$ ), the planet's phase function representing the reflected flux along the orbit ( $F_{\text{p}}$ ), Doppler beaming caused by the host star's changing radial velocity ( $F_{\text{beam}}$ ), and ellipsoidal variations resulting from stellar tides raised by the planet ( $F_{\text{ellip}}$ ).

**Approximate forms** Under the assumptions of a circular orbit, negligible luminosity for the low-mass companion, and  $M_{\text{p}} \ll M_{\star}$ , the equations describing the amplitudes of each of the three effects can be simplified (Mazeh & Faigler, 2010; Faigler & Mazeh, 2011). They are given by (Faigler & Mazeh, 2011)

$$A_{\text{beam}} = \alpha_{\text{beam}} \frac{4K}{c} \quad (6.109)$$

$$= 2.7 \alpha_{\text{beam}} \left( \frac{M_{\star}}{M_{\odot}} \right)^{-2/3} \left( \frac{P_{\text{orb}}}{\text{d}} \right)^{-1/3} \left( \frac{M_{\text{p}} \sin i}{M_{\text{J}}} \right),$$

$$A_{\text{ellip}} = \alpha_{\text{ellip}} \frac{M_{\text{p}} \sin i}{M_{\star}} \left( \frac{R_{\star}}{a} \right)^3 \sin i \quad (6.110)$$

$$= 13 \alpha_{\text{ellip}} \sin i \left( \frac{R_{\star}}{R_{\odot}} \right)^3 \left( \frac{M_{\star}}{M_{\odot}} \right)^{-2} \left( \frac{P_{\text{orb}}}{\text{d}} \right)^{-2} \left( \frac{M_{\text{p}} \sin i}{M_{\text{J}}} \right),$$

$$A_{\text{refl}} = \alpha_{\text{refl}} 0.1 \left( \frac{R_{\star}}{a} \right)^2 \sin i \quad (6.111)$$

$$= 57 \alpha_{\text{refl}} \sin i \left( \frac{M_{\star}}{M_{\odot}} \right)^{-2/3} \left( \frac{P_{\text{orb}}}{\text{d}} \right)^{-4/3} \left( \frac{R_{\text{p}}}{R_{\text{J}}} \right)^2,$$

where  $K$  is the stellar radial velocity semi-amplitude. The coefficients  $\alpha_{\text{beam}}$ ,  $\alpha_{\text{ellip}}$ , and  $\alpha_{\text{refl}}$ , are each of order unity. The numerical values are in ppm.

Figure 6.61 shows the amplitudes of the three effects for a star-planet system similar to Kepler-13 b, and a range of orbital periods. The Kepler-13 b orbital period is marked by a vertical dashed line, where the expected amplitudes are of order  $10^{-5}$  to  $10^{-4}$  in relative flux.

The folded light curve for CoRoT-3 from Mazeh & Faigler (2010), with the fitted model including reflection, beaming, and ellipsoidal effects, is shown in Figure 6.62.

**Three-harmonic model** Shporer et al. (2014) modeled the orbital modulations using a sinusoidal component at the orbital period, and two additional harmonics

$$\begin{aligned} f(t) = & a_0 + a_{1c} \cos\left(\frac{2\pi}{P} t\right) + a_{1s} \sin\left(\frac{2\pi}{P} t\right) \\ & + a_{2c} \cos\left(\frac{2\pi}{P/2} t\right) + a_{2s} \sin\left(\frac{2\pi}{P/2} t\right) \\ & + a_{3c} \cos\left(\frac{2\pi}{P/3} t\right) + a_{3s} \sin\left(\frac{2\pi}{P/3} t\right), \end{aligned} \quad (6.112)$$

where  $f$  is the relative flux,  $P$  the orbital period, and  $t$  is with respect to the mid-transit time. Compared with other formalisms (e.g. Faigler & Mazeh, 2011; Shporer et al., 2011) this introduces an additional component at the second harmonic.

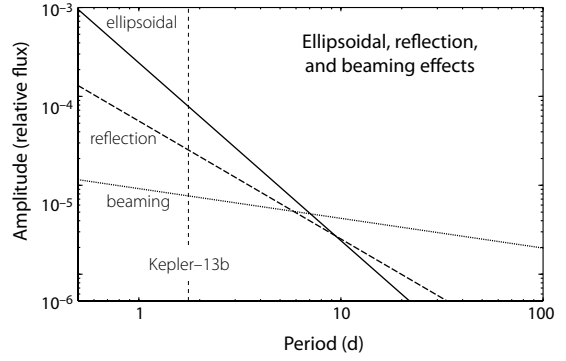


Figure 6.61: Expected amplitudes of the beaming, ellipsoidal, and reflection effects for a range of orbital periods, for a system similar to the Kepler-13 b (KOI-13.01) star-planet system. The plot based on Equations 6.109–6.111. The dashed vertical line indicates the orbital period of Kepler-13 b. From Shporer et al. (2011, Figure 1), by permission of IOP Publishing/AAS.

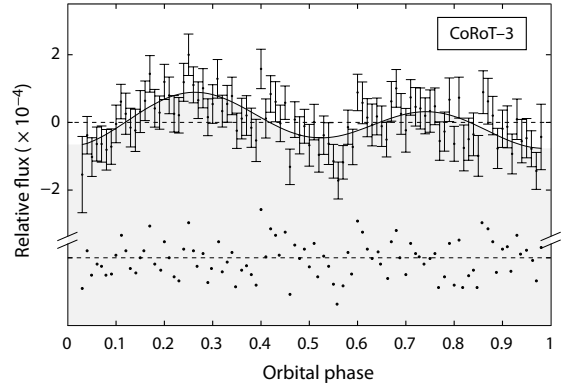


Figure 6.62: The folded light curve of CoRoT-3, with the BEER-fitted model including reflection, beaming, and ellipsoidal effects. Residuals are plotted below. From Mazeh & Faigler (2010, Figure 2), reproduced with permission © ESO.

In this (3-harmonic) model the reflection, beaming, and ellipsoidal terms have amplitudes  $a_{1c}$ ,  $a_{1s}$ , and  $a_{2c}$ , while  $a_{2s}$ ,  $a_{3c}$  and  $a_{3s}$ , not associated with any specific physical effect, were expected to be small or negligible. In the 2-harmonic model,  $a_{3c}$  and  $a_{3s}$  are set to zero.

**Mass estimates from phase modulation** The beaming and ellipsoidal amplitudes depend linearly on  $M_{\text{p}}$ . Estimates of  $M_{\text{p}}$  can be obtained from (Shporer et al., 2014)

$$M_{\text{p,beam}} \sin i = \frac{0.37}{\alpha_{\text{beam}}} \left( \frac{M_{\star}}{M_{\odot}} \right)^{2/3} \left( \frac{P_{\text{orb}}}{\text{d}} \right)^{1/3} \left( \frac{A_{\text{beam}}}{\text{ppm}} \right) M_{\text{J}}, \quad (6.113)$$

$$M_{\text{p,ellip}} \sin i = \frac{0.077}{\alpha_{\text{ellip}} \sin i} \left( \frac{R_{\star}}{R_{\odot}} \right)^{-3} \left( \frac{M_{\star}}{M_{\odot}} \right)^2 \left( \frac{P_{\text{orb}}}{\text{d}} \right)^2 \left( \frac{A_{\text{ellip}}}{\text{ppm}} \right) M_{\text{J}}, \quad (6.114)$$

where  $\sin i \approx 1$ , and  $\alpha_{\text{beam}}$  and  $\alpha_{\text{ellip}}$  are of order unity.

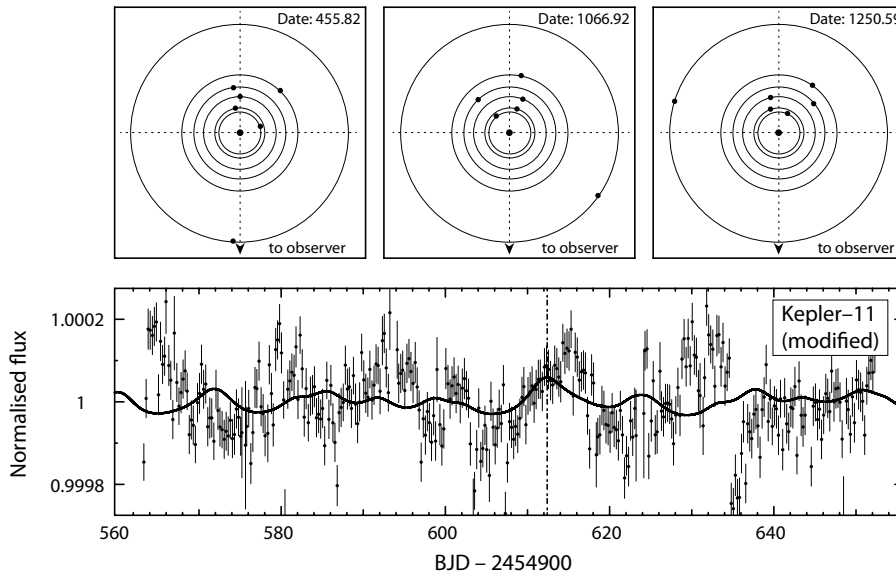


Figure 6.63: Top: projections of the Kepler-11 system showing the planet positions with respect to the line-of-sight at various times of peak phase amplitude, which occurs when most of the planets are near superior conjunction. Bottom: predicted flux variations of a modified Kepler-11 system in Q7, where the planet radii are five times larger, and the albedos double, their actual values. The vertical dashed line is the time of predicted maximum phase amplitude. Faintness of the host star is a major contributor to the scatter in the flux. From Gelino & Kane (2014, Figures 2 and 4), by permission of IOP Publishing/AAS.

Shporer et al. (2014) gave two separate mass estimates for Kepler-13A b:  $M_{p,beam} \sin i = 7.57 \pm 0.52 M_J$  and  $M_{p,ellip} \sin i = 5.94 \pm 1.00 M_J$ . Similar discrepancies have been noted in earlier results on Kepler-13A b (Mazeh et al., 2012); KOI-74 and KOI-81 (van Kerkwijk et al., 2010; Bloemen et al., 2012); the hot white dwarf KIC-10657664 (Carter et al., 2011b); TrES-2 (Barclay et al., 2012); Kepler-76 b (Faigler et al., 2013); and Kepler-8, Kepler-10, KOI-64, TrES-2 and HAT-P-7 (Esteves et al., 2013). Discrepancies may originate from inaccuracies in stellar parameters (Shporer et al., 2014).

### 6.15.7 Atmospheric effects

Deviations of the orbital phase curves from simple harmonic forms are expected to result from heat transfer in the atmosphere, as well as atmospheric structure resulting from inhomogeneous distributions of clouds and hazes. Somewhat overlapping the considerations here, this is considered further under the discussion of atmospheres (§11.6.3).

### 6.15.8 Spin-orbit tomography

Reflected light from a planet depends on the albedo of the visible and illuminated region of the planetary surface, which changes according to the spin rotation and orbit phase. One approach to resolved imaging with a single telescope is therefore to apply an inversion technique to derive a two-dimensional albedo/reflectivity

map of the planet surface from a series of diurnal and annual variations of scattered light (Ford et al., 2001b).

The inversion technique of *spin-orbit tomography*<sup>2</sup> has been applied to exoplanet imaging (e.g. Fujii et al., 2010; Kawahara & Fujii, 2010, 2011; Fujii & Kawahara, 2012; Kawahara, 2012; Berdyugina & Kuhn, 2017).

Kawahara & Fujii (2010) showed that a global map of an idealised Earth-like planet, along with its obliquity, can be reconstructed, with both longitudinal and latitudinal resolution, assuming a face-on circular orbit with known rotation rate, the absence of clouds and atmospheric absorption, static surfaces with known reflectance spectra, and the absence of a moon. They conclude that future space missions can estimate both the surface distribution and the obliquity for cloudless Earth-like planets within 5 pc.

Fujii & Kawahara (2012) extended the reconstruction to more general configurations, including low-obliquity planets in inclined orbits. Through simulated light curves of the Earth in an inclined orbit in three photometric bands (0.4–0.5, 0.6–0.7, and 0.8–0.9  $\mu\text{m}$ ), they

<sup>2</sup> Tomography (from the ancient Greek ‘*tomos*’ for slice or section, and ‘*grapho*’ to write), as used in many areas of science, refers to imaging by sections, typically using some kind of penetrating wave. In this case, a 2d image of the planet surface is reconstructed from integrated exposures taken over a range of diurnal and annual observing geometries, further facilitated if the planet’s spin axis is not directed along the line-of-sight.

showed that the distribution of clouds, snow, and continents can be retrieved, also for an Earth with spin axis  $i = 0^\circ$ , for a tidally locked Earth, and for Earth analogues with ancient continental configurations. Application to the surface imaging of Proxima Cen is detailed by Berdyugina & Kuhn (2017) confirming, for example, the prospects of resolving continent-type features.

### 6.15.9 Multi-planet systems

For multi-planet systems, phase modulation of the collective system rapidly becomes more complicated (Kane & Gelino, 2013). Although dependent on the period, radius, and albedo distributions for the various planets, Kane & Gelino (2013) showed that some decoupling may still be possible, and illustrated the predicted effects for the 5-planet systems Kepler–20 and Kepler–33.

For Kepler–11, Gelino & Kane (2014) gave predictions of maximum phase modulation where the planets are simultaneously close to superior conjunction, and found that (for Kepler Q1–Q17) there are quarters where maximum phase peaks occur which are better fit by a phase model than a null hypothesis model (Figure 6.63).

**Inclination dependence** While additional planets may dilute the signature from the dominant light-reflecting planet, the total phase function will nevertheless be dependent on the mutual orbit inclination.

For  $\nu$  And, only a marginal detection of reflected light from the inner planet has been reported (Collier Cameron et al., 2002), and there is an ambiguity in any interpretation because of the degeneracy between planet radius and assumed albedo. Astrometric constraints on the outer two planets, c and d (McArthur et al., 2010) give semi-major axes of 0.83 and 2.53 au, and inclinations  $8^\circ$  and  $24^\circ$  respectively. The factor of three increase in orbital distance of the outer planet results in a factor of 9 less contribution to the total planetary reflected light. However, their inclinations result in the phase function of the outer planet being almost 3 times that of the inner planet (Kane & Gelino, 2010).

**Resonance effects in multi-planet systems** The periodic simultaneous pericentre passage of two planets in mean motion resonance produces a distinct signature in phase amplitude, although not necessarily coinciding with epochs of maximum flux ratio. Figure 6.56e–f show two example systems, each with two Jupiter radii planets (Kane & Gelino, 2010). Given sufficient photometric precision and observing cadence, it may be possible to distinguish the deviant secondary peak of the first system and deduce the presence of the outer planet.

### 6.15.10 Algorithmic implementation

Publicly available algorithms for the modeling of primary transits, secondary eclipses, and phase curves, are given in Section 6.12.4.

## 6.16 Transits at other wavelengths

In addition to the observations of transits and eclipses at infrared wavelengths (§6.24), and bow shocks observed at ultraviolet wavelengths (§6.14.10), transit observations have been attempted at X-ray and sub-mm/radio wavelengths. This is in addition to the broader topics of detecting exoplanets at radio and mm/sub-mm wavelengths (§8.10.5) and at X-ray wavelengths (§8.10.4).

### 6.16.1 X-ray

**Introduction** Exoplanets, and especially hot Jupiters at a distance  $\lesssim 0.1$  au from their parent stars, are in a unique X-ray environment, and the effects of stellar X-rays may be significant to their evolution. X-rays have been cited as the cause of excess planetary heating, which can induce mass loss (Lammer et al., 2003). The ultraviolet/X-ray flux from the star plays a crucial role in determining the photochemistry of the planet's upper atmosphere. The photochemical products can act, in turn, as high-altitude absorbers, create thermal inversions, and otherwise alter the observable properties of the planet's upper atmosphere. These effects are important when observing at lower energies/longer wavelengths (Liang et al., 2004; Burrows et al., 2008a).

The magnetic fields of the star and the planet can also interact when the latter is orbiting at a distance of very few stellar radii as in the case of HD 189733 (Lanza, 2008, 2009; Cohen et al., 2009). The complex magnetosphere that is formed by the star/planet system can drag material from the outer atmosphere of the planet and funnel it onto the stellar surface. The accretion of gas on the star that eventually could arise from this phenomenon can provoke shocks that heats the plasma up to a few millions of degrees and thus emits in X-rays. Furthermore, the enhanced magnetic field near the stellar surface can form very active regions on the star increasing the activity of the star in the X-ray band. Statistical analysis of X-ray activity of stars possessing hot Jupiters indicates that stars with close orbiting planets show enhanced X-ray emission (Kashyap et al., 2008).

A typical hot Jupiter receives some  $2 \times 10^4$  times more radiation from its star than Jupiter does from the Sun, and orbits at a distance of only some  $10R_\star$ . Unlike solar system planets, where residual heat from formation and gravitational settling still plays an important part in the energy budgets of Jupiter and other giant planets, the energy budget for hot Jupiters is dominated by the strong radiation from their host star. This energy budget is poorly constrained in the X-ray and ultraviolet regimes by standard stellar atmosphere models.

**HD 189733** X-ray observations of HD 189733 have been made with XMM–Newton (Pillitteri et al., 2010, 2011) and Chandra–ACIS–S (Poppenhaeger et al., 2013). The latter reported a detection of the planetary transit

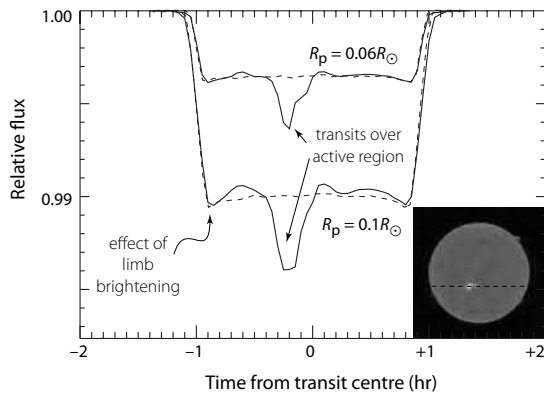


Figure 6.64: Inset: solar map at 17 GHz with an active region of brightness temperature  $\sim 1.5 \times 10^4$  K. The dashed line is the path of a putative planet, crossing the maximum activity region. Main figure: simulated light curves for transiting planets of sizes  $0.06$  and  $0.10R_{\odot}$  crossing the active solar surface (solid lines), and a quiet Sun (dashed lines). Effects of limb brightening are evident, as is the flux decrement as the planet obscures the active region. From Selhorst et al. (2013, Figures 1 and 2), by permission of IOP Publishing/AAS.

in soft X-rays, with a significantly deeper transit depth of some 6–8% compared with the broad-band optical transit depth of 2.4%. They inferred that the deep X-ray transit is probably not simply a result of coronal inhomogeneities, but is caused by a thin outer planetary atmosphere which is transparent at optical wavelengths, but dense enough to be opaque to X-rays. The X-ray radius also appears to be larger than that at far-ultraviolet wavelengths, most likely due to high temperatures in the outer atmosphere at which hydrogen is mostly ionised.

### 6.16.2 Sub-mm and radio

Transit detectability at 30–950 GHz by ALMA have used (Nobeyama Radioheliograph) solar maps at 17 GHz as proxies (Selhorst et al., 2013). In contrast with optical observations which show photospheric limb darkening, simulated transits over a quiet Sun, show *limb brightening* because of the positive chromospheric temperature gradient. And unlike star spot crossings in the optical, a transiting planet crossing active regions leads to a relative flux decrease (Figure 6.64).

For a Sun-like star at 10 pc observed with ALMA at 345 GHz with 50 antennas, Selhorst et al. (2013) estimate detectability in 1 h. Detectability will be improved for younger and more active stars, with higher brightness temperatures and larger active areas.

## 6.17 Polarisation

There are two manifestations of polarisation of direct relevance to exoplanet observations. In the first, applicable to *transiting systems*, the transiting planet breaks

the symmetry in total polarisation integrated over the stellar disk, resulting in a non-zero linear polarisation which varies through the transit. The second exploits the fact that light *reflected* from a planet (and therefore also outside of the transit or secondary eclipse phases) will typically be polarised as a result of scattering. In addition, polarisation at optical wavelengths (with the advent of imaging instruments like VLT-SPHERE) and sub-mm wavelengths (with ALMA) provides an important probe of scattering in protoplanetary, transition and debris disks, considered further in Chapter 7.

Polarimetry is likely to become an increasingly important technique for exoplanet studies, although one which is currently limited by instrumental accuracies (Kolokolova et al., 2015, see also box, page 247).

### 6.17.1 Transit effects

Light from solar-like stars has a very small overall polarisation. The integrated solar disk, for example, has a linear polarisation of less than  $2 \times 10^{-7}$  in  $V$  (Kemp et al., 1987). However, the *resolved* solar disk shows a polarisation variation from centre to limb (Leroy, 2000).

This changing linear polarisation across a stellar disk is the result of varying contributions from scattering opacity to the total atmospheric opacity, with the effect most pronounced at the stellar limb (Chandrasekhar, 1946a,b). Although the disk-integrated linear polarisation from a spherical featureless star is zero, *limb polarisation*, the bright corollary to limb darkening, arises from the  $90^\circ$  scattering angle and low optical depth experienced by photons at the stellar limb. A transiting planet breaks this symmetry, resulting in a distinct polarimetric signature during its crossing of the stellar disk.

As a result, and in contrast to photometric transits where the peak signal occurs at mid-transit due to obscuration of the brightest region of the disk, maximal polarimetric signals occur at ingress and egress (Carciofi & Magalhães, 2005; Kostogryz et al., 2011). A transiting planet introduces a typical net radial polarisation of  $10^{-6}$ . The polarisation position angle during transit is parallel to the line joining the star–planet centres, and rotates in a sense determined by the stellar hemisphere transited. Such an effect was first detected in the eclipsing binary Algol (Kemp et al., 1983).

In addition to its dependence on  $R_p/R_*$ , the polarimetric amplitude during transit is influenced by the strength and width of limb polarisation, which depend on the scattering-to-total opacity ratio at the limb.

Observations of both the Sun (Faurobert et al., 2001; Faurobert & Arnaud, 2003) and Algol (Kemp et al., 1983) have verified the prediction of limb polarisation. Although limb darkening, due to low optical depth and to photon diffusion preferentially in the plane of the sky at the limb, ensures that most limb-scattered photons do



not reach the observer, the relatively few that do will be preferentially polarised tangent to the limb.

Simulations by Carciofi & Magalhães (2005) for transits of GKM dwarfs suggested that the effect may be observable even for Earth-like planets, while asymmetries around mid-transit may further constrain  $e$ .

**Polarisation transit model** The net polarisation due to an exoplanet transiting a Sun-like star is given by the fractional circumference occulted by the exoplanet multiplied by the polarisation and limb-darkened stellar intensity (Carciofi & Magalhães, 2005; Wiktorowicz & Laughlin, 2014; Kostogryz et al., 2017). For  $R_p/R_\star \ll 1$

$$P(t) = \int_{r_p(t)-(R_p/R_\star)}^{r_p(t)+(R_p/R_\star)} \frac{C(r,t)}{2\pi r} I(r) P_\star(r) dr, \quad (6.115)$$

where  $P(t)$  is transit polarisation,  $r_p(t)$  is the position of the exoplanet centre,  $C(r,t)$  is the path length along the stellar circumference at  $r$  occulted by the exoplanet,  $I(r)$  is the limb-darkened stellar intensity, and  $P_\star(r)$  is the stellar polarisation at radius  $r$ . Simple geometric expressions for  $C(r,t)$  and  $r_p(t)$  (in terms of the impact parameter, time of mid-transit, and transit duration) are given by Wiktorowicz & Laughlin (2014, Equations 2–3).

Limb-darkened stellar intensity is expressed in terms of the angle between the line-of-sight and the normal to the stellar surface,  $\mu = \cos\theta$  (§6.14.1). Stellar polarisation is similarly modeled as

$$P_\star(\mu) = P_1 \left( \frac{1 - \mu^2}{1 + k\mu} \right), \quad (6.116)$$

where  $P_1$  is the degree of polarisation at the limb and  $k$  is the inverse of the profile width, which determines how rapidly polarisation decreases from the limb to the centre of the stellar disk (Fluri & Stenflo, 1999). The polarimetric amplitude during transit is insensitive to impact parameter  $b$ , at least for non-grazing transits (Carciofi & Magalhães, 2005; Wiktorowicz & Laughlin, 2014).

Since stellar polarisation is tangential to the limb, the polarisation position angle during transit,  $\Theta(t)$ , is equal to the projected position angle of the planet centre with respect to the stellar centre

$$\Theta(t) = \pm \arctan \left[ \frac{2t}{t_T} \left\{ \left( \frac{(1 + R_p/R_\star)^2}{b} - 1 \right)^{0.5} \right\} \right] + C, \quad (6.117)$$

where  $t_T$  is the transit duration, and  $C$  is a constant. Thus, the polarisation position angle rotates monotonically with time during the transit. Specifically, between first and second contacts it rotates by

$$\Theta_2 - \Theta_1 = \arccos \left( \frac{b}{1 + \frac{R_p}{R_\star}} \right) - \arccos \left( \frac{b}{1 - \frac{R_p}{R_\star}} \right). \quad (6.118)$$

The longitude of the planet's ascending node can also be determined, and is given geometrically by

$$\begin{aligned} \Omega &= \Theta_1 + \arccos \left( \frac{b}{1 + R_p/R_\star} \right) - 90^\circ \\ &= \Theta_2 + \arccos \left( \frac{b}{1 - R_p/R_\star} \right) - 90^\circ. \end{aligned} \quad (6.119)$$

**Star spots** Star spots can similarly result in symmetry breaking of the net polarisation (Kostogryz et al., 2015). Star spots occurring towards the limb will have a reduced projected area. Thus, while the models of Berdyugina et al. (2011) found that one large star spot, with 1% of the area of the stellar disk, can result in a polarimetric amplitude of  $3 \times 10^{-6}$ , the expected amplitude of the effect occurring near the limb is an order of magnitude lower. Repeated transits sample different projections, further diminishing their effect.

**Stellar oblateness** Stellar oblateness may be directly detectable, since the rotation of position angle during transit is determined by the morphology of the stellar limb. Bailey et al. (2010) demonstrated that the high polarisation of  $\alpha$  Leo is consistent with its oblateness determined by interferometry (McAlister et al., 2005).

**Candidate transiting planets** Carciofi & Magalhães (2005) used Monte Carlo simulations to predict the expected transit polarisation for  $1 - 2R_J$  planets orbiting G dwarfs, as well as K, M, and T dwarfs with a simplified limb-polarisation approximation.

Kostogryz et al. (2011) made simulations for three systems with high  $R_p/R_\star$  (TrES-3, WASP-4, WASP-25) assuming a solar limb polarisation appropriate for G-type stars (Trujillo Bueno & Shchukina, 2009).

Predictions for the K-type host HD 189733 were made by Kostogryz et al. (2011) assuming a pure scattering atmosphere approximation (Chandrasekhar, 1960a), and by Frantseva et al. (2012) assuming solar limb polarisation. Results differ by almost two orders of magnitude, which underlines the importance of knowing the intrinsic stellar polarisation.

Wiktorowicz & Laughlin (2014) predicted the most favourable systems for polarimetric transit detection, which include HD 189733 b and HD 209458 b (due to their bright host stars), the highly eccentric spin-orbit misaligned HD 80606 b (with its long transit duration, and extended ingress and egress phases), and the bright misaligned/retrograde oblate-host WASP-33 b.

Kostogryz & Berdyugina (2015) calculated centre-to-limb variations of intensity and linear polarisation for stars of different spectral types accounting for various opacity sources. Low-gravity cool stars, although having weaker limb darkening, should exhibit significantly larger linear polarisation in their continuum spectra as compared to solar-type stars, while for stars with the

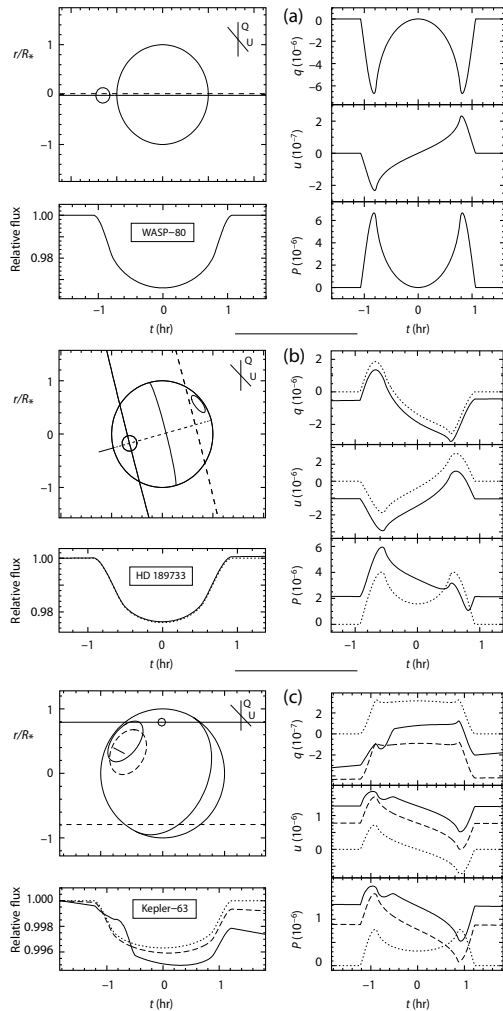


Figure 6.65: Predicted polarisation for three transiting planets. In each, the top left panel illustrates the transit configuration (the dashed line indicates the rear part of the orbit, and the positive directions of the Stokes  $q \equiv Q/I$  and  $u \equiv U/I$  are shown at the top right), the bottom left panel is the transit light curve, and the right panels show the simulated variations of the flux and the polarisation ( $q$ ,  $u$ , and  $p$ ) at  $\lambda = 450$  nm. (a) WASP-80 ( $\Omega = 90^\circ$ ). The planet orbits from left to right in front of the star. (b) HD 189733 ( $\Omega = 195^\circ$  and  $i = 94.49^\circ$ ). The planet orbits from bottom to top in front of the star. Results are shown for a star without spots (dotted lines), and with a spot added near the stellar limb (solid lines). (c) Kepler-63. Results are shown for the planet transit alone (dash-dotted lines), with a star spot outside the planet path (dashed lines), and with a spot-crossing event (solid lines). From Kostogryz et al. (2015, Figures 6, 9, 10), by permission of IOP Publishing/AAS.

same  $T_{\text{eff}}$ , limb polarisation is larger for the lower gravity giants. Effects for planets transiting T and L brown dwarfs are given by Sengupta (2016b).

Kostogryz et al. (2015) used the models of Kostogryz & Berdyugina (2015) to predict linear polarisation curves for 88 known transiting exoplanets (Figure 6.65).

**Observations** Various transit polarisation measurement attempts have been reported, including TrES-2 with OPTIMA (Słowikowska et al., 2011), and HD 80606 with POLISH2 (Wiktorowicz & Laughlin, 2014).

Detection of polarised light was first reported for HD 189733 (Berdyugina et al., 2008, 2011), although not confirmed in the same object by Wiktorowicz (2009) nor, with 50 nights of polarimetric observations with POLISH2 at the Lick 3-m telescope, by Wiktorowicz et al. (2015), nor with AAT-HIPPI (Bott et al., 2016). Whether these differences can be reconciled by some combination of wavelength dependency (cf. Evans et al., 2013), or variability, remains to be demonstrated.

### 6.17.2 Scattered light

The second manifestation of polarisation being applied to exoplanet studies involves the polarised light *reflected* from a planet outside of transit or secondary eclipse. This may be from the integrated light (also in the infrared), or directly from the planet itself if this can be resolved. Various models have been presented (e.g. Buenzli & Schmid, 2009; Zuger et al., 2010; Karalidi et al., 2011; Karalidi & Stam, 2012; Natraj & Hovenier, 2012; Kolokolova & Mackowski, 2012; Karalidi et al., 2013; Schworer & Tuthill, 2015), including results from space-based (PARASOL) polarimetric observations of Earth (Song & Qu, 2016, 2017), and from brightness curves during a Messenger fly-by in 2005 (García Muñoz, 2015).

These studies suggest that the effect should be measurable in various exoplanet systems, allowing further characterisation of their atmospheres and orbits (Seager et al., 2000; Tamburini et al., 2002; Baba & Murakami, 2003; Saar & Seager, 2003; Stam et al., 2004, 2006; Stam, 2008; Fluri & Berdyugina, 2010; de Kok et al., 2011b; Fauchez et al., 2017; Takahashi et al., 2017).

Light scattered in the planet's atmosphere (by gas molecules, clouds, hazes, aerosols, and dust grains), or from its surface, is linearly polarised perpendicular to the scattering plane, with details depending on orbital characteristics, on the nature and geometry of the scattering particles, and on the observation wavelength. The polarised component will be modulated through the full range in orbital phase angles (e.g. Seager et al., 2000; Stam et al., 2004; Wiktorowicz, 2009; Fluri & Berdyugina, 2010; Rossi & Stam, 2017; Stolker et al., 2017). As for reflected light studies, orbits closer to the star are more favourable (Figure 6.66).

Characterised by the Stokes parameters  $Q$  and  $U$ , these parameters will vary as the scattering angle changes, and should show two peaks per orbital period. Polarisation variability would constrain the nature of scattering particles in the planetary atmosphere, and allow determination of  $P$ ,  $e$ , and  $i$ ; the latter, in combination with radial velocity measurements, would resolve the  $M_p \sin i$  degeneracy.

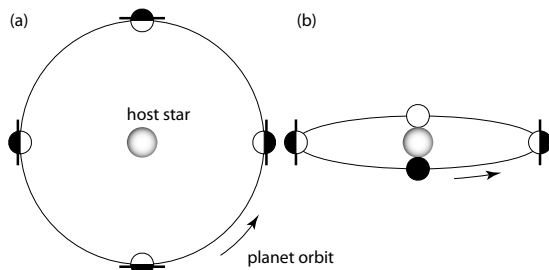


Figure 6.66: Polarisation modulation due to scattered light, which is represented by the white (illuminated) portion. The position angle of net polarisation is shown by the black lines. For a face-on circular orbit (a), the planet is always at quarter phase, and the degree of polarisation remains constant although its position angle rotates through  $360^\circ$ . An edge-on orbit (b) results in variability in the degree of polarisation because the amount of scattered light is variable, but the scattering plane is always co-planar with the orbital plane, so the position angle of net polarisation does not vary. From Wiktorowicz (2009, Figure 1), by permission of IOP Publishing/AAS.

For an unresolved star–planet system, any net polarisation will be very small,  $\lesssim 10^{-5}$ , largely dictated by the ratio of reflected to total light, and with a strong dependency on the structure of the planetary atmosphere (Stam, 2004). Despite the small effect, a high (relative) accuracy is nevertheless possible from the ground.

The measurement of scattered light is not restricted to transiting systems. Nevertheless, transiting systems may allow the most rigorous demonstration of detection, since variability due to instrument, telescope, sky, interstellar medium, and host star can be assessed during secondary eclipses (Wiktorowicz & Laughlin, 2014).

Ignoring polarisation will affect the interpretation of reflected light studies and phase curves (§6.15) more generally, especially for elliptical orbits, or if the planet is oblate (Stam & Hovenier, 2005; Sengupta & Maiti, 2006).

**Candidate planets** Milli et al. (2013) performed simulations to identify candidates for imaging and polarisation with SPHERE–ZIMPOL. Of the known planets with  $M_p < 25M_\oplus$ , they identified  $\alpha$  Cen B b as their favoured target. Assuming a gaseous Rayleigh-scattering atmosphere and favourable inclinations, the planet could be detected in 4 h using the four-quadrant phase-mask coronagraph in the  $I$  band.

Sun et al. (2013) and Qu et al. (2013) used photometric and polarimetric phase curves of Mercury and Venus to predict the polarimetric detectability and characterisation of unresolved Mercury- and Venus-like planets.

**Self-luminous giant planets** A number of young self-luminous giant planets, orbiting at large distances from their host star, have been directly imaged (Chapter 7), and are inferred to be dusty. These dusty atmospheres have been conjectured to exhibit detectable linear polarisation in the near-infrared, as observed for some

**Polarimeters:** Detection of linear polarisation from atmospheric scattering, or from stellar symmetry breaking caused by a transiting exoplanet, calls for very accurate polarimetry. The most accurate polarimetric observations were made for the Sun (Kemp et al., 1987), reaching a sensitivity of parts in ten million, although current state-of-the-art on other stars does not yet attain this accuracy. Current instruments used for exoplanet studies include:

- DIPOL-2 (Double Image Polarimeter) is a broad-band polarimeter with a precision of  $10^{-5}$  (Piirola et al., 2014).
- ExPo (Extreme Polarimeter) is a dual-beam polarimeter, operating at the WHT, currently reaching contrast ratios of  $10^{-5}$  (Canovas et al., 2011).
- HIPPI (High Precision Polarimetric Instrument), commissioned at the AAT in 2014, is designed to measure stellar polarisation at the ppm level, and optimised at blue wavelengths for exoplanet applications. It includes ferroelectric liquid crystal modulators, 3d printed components, and ultra-bialkali photomultipliers (Bott et al., 2016).
- OPTIMA (Optical Pulsar Timing Analyser) is a high-speed single photon counting photo-polarimeter, designed to observe sources that radiate mainly at X- and gamma-ray energies (Kanbach et al., 2008).
- PlanetPol, an APD-based polarimeter designed to detect unresolved planets, reaches a relative sensitivity of  $10^{-6}$  on bright targets, although with larger systematics (Hough et al., 2003, 2006a,b; Lucas et al., 2009; Bailey et al., 2010).
- POLISH1 (POLarimeter for Inclination Studies of High mass x-ray binaries/Hot Jupiters) is a visible light polarimeter commissioned at the Hale 5-m telescope.
- POLISH2, at the Lick–Shane 3-m telescope, reported a precision of  $\sim 10^{-5}$  (Wiktorowicz & Laughlin, 2014).
- SPHERE (Spectro-Polarimetric High-contrast Exoplanet REsearch instrument) combines adaptive optics (§7.6.2), spectroscopy and coronagraphy with an imaging polarimeter (ZIMPOL). SPHERE targets a polarimetric sensitivity of  $\sim 10^{-5}$  (Beuzit et al., 2006; Thalmann et al., 2008a; Milli et al., 2013). It became operational in June 2014.
- ZIMPOL (Zurich Imaging Polarimeter) has achieved a relative sensitivity of  $10^{-6}$  in solar spectropolarimetry (Stenflo et al., 2000). It is one of the components of the SPHERE imaging instrument (see above).

In addition, SPICES (Spectro-Polarimetric Imaging and Characterisation of Exoplanet Systems) was a proposed ESA mission, targeting a coronagraph for the spectropolarimetric analysis of giants, super-Earths and circumstellar disks in visible light at  $R \sim 40$  (Boccaletti et al., 2012; Maire et al., 2012a). LOUPE, an instrument on the Moon to serve as a verification of exoplanet diagnostics, was described by Karalidi et al. (2012b).

field L dwarfs, arising either from rotationally-induced oblateness, or from surface inhomogeneities such as partial cloud (Sengupta, 2013; Marley & Sengupta, 2011).

Marley & Sengupta (2011) used a homogeneous atmospheric model with multiple scattering polarisation to show that polarisation of  $\sim 1\%$  may arise due to their rotation-induced oblateness, that the polarisation for cloudy planets should peak at the same wavelengths at which the planets are brightest in the near-infrared, and that polarised radiation would provide a new method to constrain their surface gravity and masses.

**Exomoons around self-luminous giant planets** The additional asymmetry introduced by the presence of an orbiting satellite (§6.22) could lead to peak polarisation signals between 0.1–0.3% in the infrared, making such exomoons detectable through time-resolved imaging polarimetry (Sengupta & Marley, 2016).

**Results** Various attempts to identify planet scattering effects through polarisation have been reported. They have generally been either unsuccessful, or challenged.

Berdyugina et al. (2008) reported the detection of polarised light from HD 189733 b during transit. *B* band measurements with DIPOL on the 0.6-m KVA telescope, La Palma, distributed over orbital phase, gave two polarisation peaks near maximum predicted elongation with an amplitude of  $2 \times 10^{-4}$ . Fixing  $P$ ,  $a$ ,  $R_p$ , and  $T_0$ , they found  $i$  and  $e$  in agreement with radial velocity-derived values, and a (Lambert) radius of the scattering atmosphere 30% larger than that of the opaque body inferred from transits. While a possible explanation was quickly forthcoming (Sengupta, 2008), the measurements have not been confirmed (Wiktorowicz, 2009).

Lucas et al. (2009) reported observations of 55 Cnc and  $\tau$  Boo at the WHT 4.2-m telescope with Planetpol. Their measured nightly standard deviation on  $Q$  and  $U$  was  $2.2 \times 10^{-6}$ , but they derived only upper limits on the polarised flux for 55 Cnc  $e$  and  $\tau$  Boo  $b$ .

A 2-year BVRI polarimetric monitoring of 51 Peg was reported by Antonyuk et al. (2013).

**Circular polarisation and life** Further in the future, circular polarisation spectroscopy could provide a remote-sensing technique in the search for life. This consideration is based on *homochirality*, in which biogenic molecules are presumed likely to possess the same sense of chirality (enantiomorphism), and with the same sense of circular polarisation when viewed in scattered light (e.g. Sparks et al., 2009; Berdyugina et al., 2016).

## 6.18 Rossiter–McLaughlin effect

### 6.18.1 Context

**Heritage from eclipsing binaries** Two papers in the *Astrophysical Journal* in 1924 reported anomalies in the velocity curves of the binary systems  $\beta$  Lyr (Rossiter, 1924) and Algol (McLaughlin, 1924). For the 12.9 d  $\beta$  Lyr system, a secondary oscillation in an interval of  $\pm 1.6$  d on either side of the principal minimum was apparent from 442 spectra taken over 1911–21.

Appealing to the rotation of the eclipsed star, normally symmetrically broadened by the rotation of one limb away from the observer and the other toward, Rossiter explained the effect as ‘*When the star is entering eclipse, the receding limb is visible and the approaching limb is covered [and vice versa]*’, leading to an asymmetry in the velocity curve. Described by them as the

‘*rotational effect*’, its magnitude amounted to 26 and 35 km s<sup>-1</sup> in  $\beta$  Lyr and Algol respectively.

Described in the exoplanet literature as the *Rossiter–McLaughlin effect*, and sometimes as the Holt–Rossiter–McLaughlin effect, the phenomenon, and its possible rotational origin, had previously been noted by Schlesinger in the cases of both  $\delta$  Lib (Schlesinger, 1910, p134) and  $\lambda$  Tau (Schlesinger, 1916, p28) and, as noted by Heller et al. (2009), predicted by Holt (1893). Further contributions were made by Hosokawa (1953). More on the historical background is given by Albrecht (2012).

**Application to exoplanets** An analogous effect occurs during an exoplanet transit, as shown schematically in Figure 6.67. As the planet transits its rotating host star, it blocks out more of the star’s rotationally blueshifted light at A, and more of its redshifted light at C, causing changes in the radial velocity profile according to orbital phase. As a consequence, in addition to the photometric transit signal, a small spectroscopic signal accompanies the basic orbital Doppler shift.

As suggested by Schneider (2000), the effect should then be seen during transit as a (positive or negative) anomaly in the radial velocity curve, caused by the progressive occultation of the rotating stellar disk.

The effect was first reported by Queloz et al. (2000a) for HD 209458 ( $\lambda = 4^\circ \pm 20^\circ$ ). Measurements have since been made for a growing number of systems (§6.18.7).

**Astrophysical relevance** The radial velocity deviations from a Keplerian fit provides constraints on the *stellar obliquity*,  $\psi$ , viz., the star’s spin axis orientation with respect to the planet’s orbit plane (Figure 6.68).

Although the orbit planes of all eight solar system planets are reasonably well aligned with the solar equator (§12.4), such alignment is not the rule for exoplanets. Of the theories proposed to explain the close-in giant planets, migration through a gaseous disk should broadly preserve the initial spin–orbit alignment, or even lead to a reduction in any primordial misalignment (§10.10.2). In contrast, both planet–planet scattering (§10.10.4) and/or Lidov–Kozai oscillations (§10.10.6), followed in either case by tidal circularisation for close-orbiting systems (§10.10.6), are expected to result in a misalignment in the relative orientation between the stellar spin axis and the orbital plane.

### 6.18.2 Formalism

Measurement of the angle  $\psi$  between the planet’s orbit axis and the spin axis of its host star therefore provides diagnostics of theories of planet formation and subsequent evolution. Yet while the inclination of the planet orbit  $i \approx 90^\circ$  is measured via transit photometry, the orientation of the stellar rotation axis in space is generally unknown. As a result,  $\psi$  cannot be measured directly using the Rossiter–McLaughlin effect, but only the angle  $\lambda$

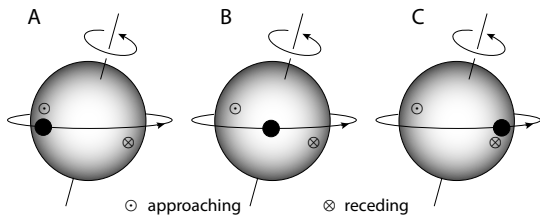


Figure 6.67: Schematic of the Rossiter–McLaughlin effect during a planetary transit: as the exoplanet transits its rotating host star, it blocks out more of the star’s rotationally blueshifted light at A, and more of its redshifted light at C, causing changes in the radial velocity profile according to orbital phase.

between the sky projections of the orbital and stellar rotation axes (Figure 6.69). Furthermore, by symmetry, the configuration  $(i, \lambda)$  is observationally indistinguishable from  $(\pi - i, -\lambda)$  (Fabrycky & Winn, 2009, §2).

Positive  $\lambda$  implies that, from the observer’s perspective, the projected stellar spin axis is rotated clockwise with respect to the projected orbit normal. Values  $|\lambda| > (\pi - i)$  imply retrograde orbits (Fabrycky & Winn, 2009).

Spectroscopic interpretation is variously based on a modeled stellar photosphere (Queloz et al., 2000a; Winn et al., 2005), or analytic expressions depending on the assumed form of limb darkening (Ohta et al., 2005; Giménez, 2006b). Improvements in modeling the stellar absorption line profiles have led to improved analytical estimates of the amplitude of the radial velocity anomaly. These have taken detailed account of stellar rotation and macroturbulence, as well as instrumental and astrophysical sources of line-broadening (Fabrycky & Winn, 2009; Pont, 2009; Simpson et al., 2010b; Hirano et al., 2010, 2011c; Boué et al., 2013). Different models are compared by Brown et al. (2017a).

While the framework here refers to the angle  $\lambda$  as defined by Ohta et al. (2005) and most widely-used subsequently, others have used the angle  $\beta = -\lambda$  as defined and used by Hosokawa (1953) and Giménez (2006b).

**Size of the effect** Because the Rossiter–McLaughlin effect arises from the differential occultation of Doppler-shifted stellar limbs, the semi-amplitude scales with the projected stellar rotation velocity,  $v \sin i$ , and the transit depth. The maximum amplitude of the radial velocity anomaly is (Winn, 2010, eqn 40)

$$\Delta V \approx \left( \frac{R_p}{R_\star} \right)^2 \sqrt{(1 - b^2)} v \sin i_\star, \quad (6.120)$$

where  $v \sin i_\star$  is the projected stellar equatorial rotation velocity. Because the transit observations give a precise and independent measure of  $(R_p/R_\star)^2$ , spectroscopic monitoring of  $\Delta V$  therefore tracks the planet’s trajectory referred to the sky-projected stellar rotation axis. The form of Equation 6.120 indicates that, ignoring the ef-

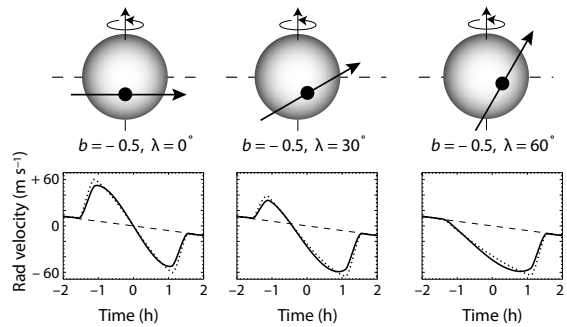


Figure 6.68: Three different transit trajectories, with the same impact parameter and therefore the same light curves, showing the dependence of the Rossiter–McLaughlin radial velocity signature on  $\lambda$ , computed with the formulae of Ohta et al. (2005). The long-dashed lines show the star’s radial velocity in the absence of the Rossiter–McLaughlin effect. Solid and dotted lines are with and without limb darkening. Adapted from Gaudi & Winn (2007, Figure 2), by permission of IOP Publishing/AAS.

fects of rotational line broadening, giant planets around rapidly rotating stars provide optimal candidates.

For a Sun-like star, with  $v \sin i \approx 2 \text{ km s}^{-1}$ , the maximum effect is  $\sim 20 \text{ m s}^{-1}$  for  $R_p = R_J$ , and  $\sim 0.2 \text{ m s}^{-1}$  for  $R_p = R_\oplus$ . Effects can be much larger, specifically for large  $R_p/R_\star$  or  $v \sin i_\star$ . For the bright rapidly-rotating F star KELT-7 ( $V = 8.5$ ,  $v \sin i_\star = 73 \text{ km s}^{-1}$ ),  $\Delta V \sim 200 - 300 \text{ m s}^{-1}$  (Bieryla et al., 2015, their Figure 7).

**Earth-mass planets** The form of Equation 6.120, with its dependency on transit depth, indicates that determination of the effect for Earth-mass planets around solar-type stars will be challenging. The signal improves for lower mass stars, and may be detectable in the innermost of the Earth-mass planets orbiting the late M dwarf TRAPPIST-1 (§6.4.3), and around the ultra-cool dwarfs targeted by the SPECULOOS transit survey (§6.4.4) more generally. For TRAPPIST-1, Cloutier & Triaud (2016) estimate that the star’s rapid rotation leads to Rossiter–McLaughlin semi-amplitudes of  $40 - 50 \text{ m s}^{-1}$ , an order-of-magnitude greater than the planets’ expected Doppler semi-amplitudes, with the additional prospect of measuring the chromatic dependency from the presence of atmospheric absorbers.

**Chromatic effects** The wavelength dependence, or *chromatic Rossiter–McLaughlin effect*, follows from the first-order expression for its amplitude (Equation 6.120). Since the amplitude depends on the planet’s effective radius, which is wavelength dependent (at least for transiting planets with observable transmission features), it follows that the Rossiter–McLaughlin amplitude is also wavelength dependent, and can therefore act as an atmospheric probe (e.g. Snellen, 2004; Dreizler et al., 2009; Czesla et al., 2012; Di Gloria et al., 2015).

Observed in the Ca II H and K emission-line cores of CoRoT-2A, Czesla et al. (2012) referred to this as

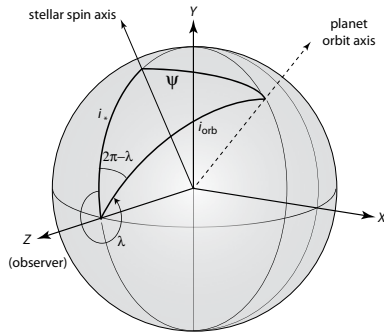


Figure 6.69: Schematic illustration of a misaligned star–planet system showing the angles of relevance. The planet’s orbit axis projected onto the sky plane is specified by the projected spin-orbit angle,  $\lambda$ , which is measured from the  $+Y$ -axis in the direction of the arrow, and lies in the range  $[0^\circ, 360^\circ]$ .  $\psi$  is the angle between the stellar spin and the planetary orbit axis vectors. Adapted from Benomar et al. (2014, Figure 1).

the *chromospheric Rossiter–McLaughlin effect*. Di Gloria et al. (2015) exploited this spectral dependence to probe the broad-band spectral signature of the optical transmission spectrum in HD 189733 b. Yan et al. (2015c) used the effect to characterise Earth’s atmosphere, using HARPS during a lunar eclipse. After correcting for solar limb darkening and convective blueshift, they detected both the  $O_3$  Chappuis band absorption, as well as Rayleigh scattering features.

**Effect of star spots** Oshagh et al. (2016) examined the impact of the occultation of star spots by the transiting planet on the estimation of  $\lambda$ . They found errors of up to  $30^\circ$ , particularly for small, aligned, edge-on planets, degrading further for longer time sampling. The effect may in part explain some of the conflicting results that have been reported. Observation at longer wavelengths, in the near infrared, is expected to improve the accuracy.

**Algorithmic implementation** A publicly-available code, AROME, determines the predicted radial velocity signature from the planet and star orbit parameters at the time of observation (Boué et al., 2013). An example implementation is given by Di Gloria et al. (2015). A differential least-squares deconvolution method is described by Strachan & Anglada-Escudé (2017).

**Constraints on true obliquity** This is considered in Section 8.3.2.

### 6.18.3 Higher-order effects

Other effects which give rise to radial velocity variations in the host star, but not specifically related to transiting planets, are considered in Chapter 2, including gravitational redshift variations (§2.5.1), Zeeman effect (§2.5.2), and planet-induced tides (§2.5.3). The latter is also relevant for many transiting hot Jupiters, but again not restricted to the transit phase.

**Planet rotation** Planet rotation leaves its own imprint on the transit spectrum. During ingress and egress, absorption features from the planet’s atmosphere are Doppler shifted by (of order) the planet’s rotational velocity,  $\sim 1\text{--}2\text{ km s}^{-1}$ . For HD 209458 b, such a rotation should result in a centroid shift of  $0.6\text{ m s}^{-1}$  on the stellar absorption lines. Spiegel et al. (2007) concluded that planet rotation could be detected at  $S/N=5$  by integration across many transits over several years with a 6-m telescope, and within 2 months with a 30-m telescope.

**Atmospheric circulation** Doppler signatures exhibiting superposed blueshifted and redshifted components are also expected to arise from atmospheric circulation, e.g. in the case of HD 209458 b (Showman et al., 2013a).

**Stellar features** Various other higher-order effects arise from the selective blocking of the stellar disk by the orbiting planet. Differential spectroscopy can, in principle, provide stellar spectra of those surface segments that were hidden behind the planet (e.g. Seager & Sasselov, 2000; Brown, 2001b; Hirano et al., 2011c; Albrecht et al., 2012b; Dravins et al., 2017a). Results for HD 209458 were reported by Dravins et al. (2017b).

**Effects** Effects accessible include (Figures 6.70):

- *line broadening due to microturbulence*, along with collisional broadening and Zeeman splitting: Albrecht et al. (2012b) account for the former by convolving the rotationally-broadened line with a Gaussian, and for the latter by convolving the disk-integrated line profiles with a Lorentzian of width  $1\text{ km s}^{-1}$ ;
- *macroturbulence*, a more complex effect which depends on the angle between the line-of-sight and the local surface normal: in the semi-analytic description by Hirano et al. (2011c), as used by Albrecht et al. (2012b), the macroturbulent field is parameterised by  $\zeta_{RT}$ , the average value of the radial and tangential velocities. Values of  $\zeta_{RT}$  as a function of  $T_{\text{eff}}$  are given by, e.g., Gray (1984, eqn 4) and Valenti & Fischer (2005);
- *differential stellar rotation*: this is included in the modeling of the WASP-7 high-obliquity transit by Albrecht et al. (2012a), who consider that its inclusion is valid if the transit chord spans a wide range of stellar latitudes, if the Rossiter–McLaughlin effect is detected with very high signal-to-noise, and if suitable prior constraints are available for limb darkening;
- *atmospheric convective blueshift* (§2.2.4): being strongest in light from the centre of the disk, and weaker near the stellar limb, disk integration leads to a small overall Doppler shift (of order  $1\text{ km s}^{-1}$ ) and an asymmetry in the stellar absorption lines, with a time dependency on the motion of the transiting planet (Shporer & Brown, 2011; Cegla et al., 2016b). The effect is included in the modeling by, e.g., Albrecht et al. (2012a,b).

**Exomoons, exorings and binary planets** The effect of an orbiting exomoon on the Rossiter–McLaughlin effect is considered in the context of exomoon signatures more generally (§6.22.1). Effects of exorings are considered by de Mooij et al. (2017). The signature of a binary planet (§6.14.4) is considered by Zhuang et al. (2012).

**Gravitational microlensing** Effects of microlensing on the Rossiter–McLaughlin effect, due to the orbiting

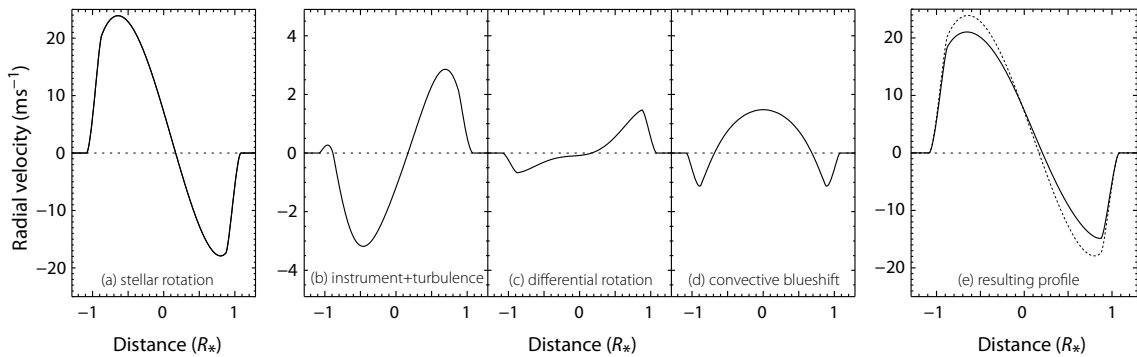


Figure 6.70: Higher-order effects influencing the Rossiter–McLaughlin profile (the abscissa gives the planet location relative to its position at inferior conjunction): (a) rotation (for  $\lambda = 40^\circ$ ,  $v \sin i_\star = 3 \text{ km s}^{-1}$ ,  $R_p/R_\star = 0.12$ , and impact parameter  $b = 0.2$ ); (b) instrumental line broadening ( $2.2 \text{ km s}^{-1}$ ) and macroturbulence ( $\zeta_{\text{RT}} = 3 \text{ km s}^{-1}$ ); (c) solar-like differential rotation; (d) solar-like convective blueshift; (e) the combination of all effects, with the dashed line that of rotation alone (panel a). From Albrecht et al. (2012b, Figure 1), by permission of IOP Publishing/AAS.

planet, have been considered by Oshagh et al. (2013b). In addition to the effect on the transit photometry (§6.14.12), the effect on the radial velocity may be significant for massive planets on long-period orbits, and may lead to underestimates of the stellar rotational velocity if unaccounted for, but should not disturb the measurement of the misalignment angle.

#### 6.18.4 Transit of Venus

The transit of Venus of 2012 June 6 allowed detection of the Rossiter–McLaughlin effect in the Sun. HARPS observations by Molaro et al. (2013) showed a modulation in the observed radial velocity with a negative amplitude of order  $-1 \text{ m s}^{-1}$  (their Figure 4), consistent with theoretical models. They assumed  $\lambda_{\text{Venus}} = 3^\circ 86$ , as derived from the JPL Horizons ephemeris.

#### 6.18.5 Rossiter–McLaughlin at secondary eclipse

During primary transit, portions of the rotating stellar surface are successively obscured, leading to the suppression of particular radial velocity components from the stellar broadened absorption lines, and hence to a time-varying radial velocity anomaly. A similar effect occurs for a rotating planet at secondary eclipse: as the planet passes behind the star, light from the approaching and receding parts of the rotating planet surface enter or exit the geometric shadow of the star. Blocking of light from the approaching (blueshifted) or receding (redshifted) regions cause time-varying distortions in the planet’s spectral line profile, and to a corresponding anomaly in the planet’s radial velocity depending on its rotation rate, axial tilt, and spin–orbital alignment.

Nikolov & Sainsbury-Martinez (2015) detailed the effect, which they denoted the *RMse effect*, derived the

resulting radial velocity curve and, assuming suitable future instrumentation, demonstrated its potential to constrain planet rotation rates and obliquities.

#### 6.18.6 Line-profile (Doppler) tomography

**Rapidly-rotating stars** In hot and rapidly-rotating host stars, the spectral lines are significantly broadened by rotation, resulting in the blending of individual lines. Such stars pose a challenge for high-accuracy radial velocities, and consequently for transiting planet validation by Doppler techniques. Rapid stellar rotation also affects, or even inhibits, the measurement of spin–orbit alignment by means of the Rossiter–McLaughlin effect.

If the stellar line profile is resolved by the spectrograph, the planet blocks light from the star during the transit, and this shows up in the line profile as a travelling ‘bump’ of width equal to that of the local non-rotating line profile. The resulting cross-correlation function used to estimate the radial velocity is asymmetric and time-varying during transit, introducing systematics which become greater for more rapidly rotating stars as their line profiles exhibit higher rotational broadening (Winn et al., 2005, 2006b, 2007e; Triaud et al., 2009; Simpson et al., 2010b; Hirano et al., 2011c).

**Modeling** The effect is exploited in the related technique of *line-profile tomography*, also referred to as *Doppler tomography*. The former term was introduced by Collier Cameron et al. (2010b) to avoid confusion with the term Doppler imaging/tomography when used to reconstruct stellar surface brightness distributions from time-series spectroscopy (box, page 440), although the latter has been more widely adopted since.

The method, which does not require high-accuracy radial velocities although it does require a suitably high S/N ratio, is based on modeling the global shape of the

stellar cross-correlation function as the convolution of a limb-darkened rotation profile and a Gaussian representing the Doppler core of the average photospheric line profile. The light blocked by the planet during the transit is a Gaussian of the same intrinsic width.

The planet's travelling 'Doppler shadow' creates distorted line profiles, which yield self-consistent measures of the projected stellar rotation velocity, the width of the mean local photospheric line profile, the projected spin-orbit misalignment, and the system's barycentric velocity (Collier Cameron et al., 2010a,b).

**Systems measured with Doppler tomography** The first systems characterised in this way were HD 189733 b (Collier Cameron et al., 2010a), WASP-33 b (Collier Cameron et al., 2010b), WASP-3 b (Miller et al., 2010), and CoRoT-11 b (Gandolfi et al., 2012). The first hot Jupiter found to transit an A-type star, WASP-33 b, was validated by Doppler tomography rather than radial velocities (Collier Cameron et al., 2010b).

The technique has since been employed either to measure the projected obliquity of a number of (mostly hot Jupiter) planetary systems orbiting early-type stars, and/or in some cases to validate the candidate transiting planet's existence in cases where radial velocity confirmation is problematic because of the rapid stellar spin (e.g., HAT-P-57, KELT-17, Kepler-448, and others). Such validation exploits the fact that the line profile variation during transit is an effective discriminant between true planets and false-positives due to eclipsing binaries.

A further improvement, termed the *Rossiter-McLaughlin effect reloaded*, uses prior information on the transit flux modulation to help isolate the planet's signature (Cegla et al., 2016a). Cegla et al. (2016a) applied the technique to HD 189733, while Bourrier et al. (2017a) used it for their observations of WASP-8.

The success of Doppler tomography has also resulted in KELT and WASP giving attention to hotter candidate stars.

Other systems measured include CoRoT-11 (Gandolfi et al., 2012), HAT-P-27 (Brown et al., 2012b), HAT-P-41 (Johnson et al., 2017c), HAT-P-56 (Zhou et al., 2016b), HAT-P-57 (Hartman et al., 2015a), HAT-P-67 (Zhou et al., 2017a), HD 189733 (Collier Cameron et al., 2010a), KELT-7 (Zhou et al., 2016b), KELT-17 (Zhou et al., 2016c), Kepler-13A (Johnson et al., 2014b), Kepler-25 (Albrecht et al., 2013), Kepler-448 (Bourrier et al., 2015a; Johnson et al., 2017c), WASP-3 (Miller et al., 2010), WASP-32 (Brown et al., 2012b), WASP-33 (Collier Cameron et al., 2010b; Johnson et al., 2015a), WASP-38 (Brown et al., 2012b), WASP-79 (Johnson et al., 2017c), WASP-167/KELT-13 (Temple et al., 2017), and XO-6 (Crouzet et al., 2017).

### 6.18.7 Results

**Measured systems** TEPCAT is an online compilation of Rossiter-McLaughlin measurements, including values of  $\psi$  (Table 1.4). As of the end of 2017, the compilation listed 198 measurements for 119 transiting planets, of which some 30–40 show significant misalignments<sup>3</sup>. Because of the high signal-to-noise spectroscopic observations required, measured planets are dominated

<sup>3</sup> The definition of 'aligned' or 'misaligned' is naturally somewhat arbitrary. Smith et al. (2013) suggest that systems may be regarded as misaligned if, at  $3\sigma$  confidence,  $\lambda > 10^\circ$ .

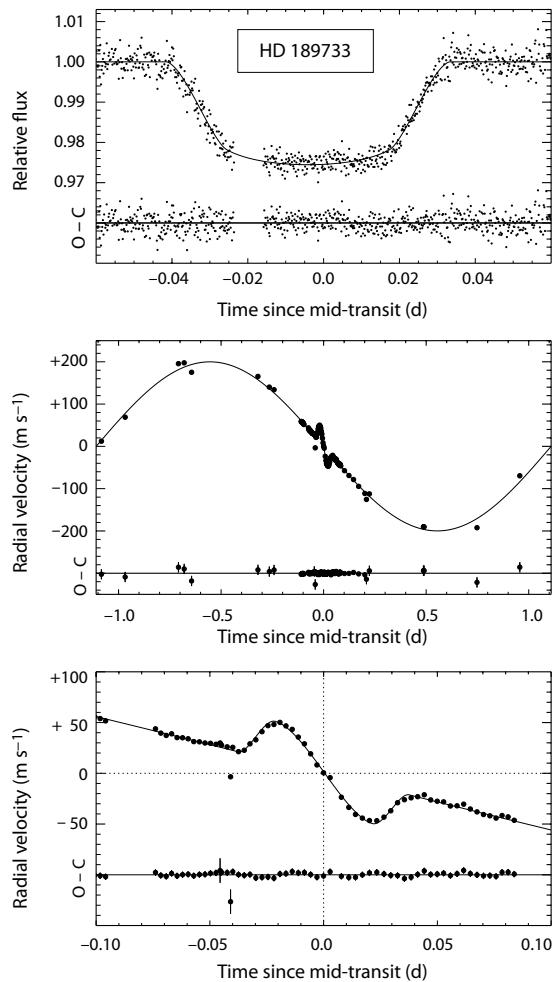


Figure 6.71: Rossiter-McLaughlin effect for HD 189733. Top: transit photometry in the z-band, with the best-fitting model (solid line). Middle: radial velocities as a function of orbital phase, along with the model (solid line). Bottom: close-up near the mid-transit time (residuals below). The abscissa scale is different in each case. From Winn et al. (2006b, Figure 1), by permission of IOP Publishing/AAS.

by the bright star transiting systems discovered by HAT/HAT-South (26 planets) and WASP (52 planets). Others include 6 CoRoT planets, 7 from KELT, 9 from Kepler, 2 from K2, 3 from TrES, and 3 from XO.

Table 6.2 lists only the WASP planets for which the effect has been measured, with results and methodologies spanning the earliest observations made in 2000 up to the present. This gives an indication of the types of results achieved to date, including the value of  $\lambda$  and its indicated error, along with spectrograph used.

Examples of the measured Rossiter-McLaughlin effect are shown in Figure 6.71 for the case of HD 189733, with a compilation of others from Magellan-PFS illustrating some different profiles shown in Figure 6.72.



Table 6.2: The WASP exoplanets (as an illustrative subset of all systems measured) for which the Rossiter–McLaughlin effect has been estimated (including values of the projection angle derived from star spot modeling). The projection angle  $\lambda$ , and its error  $\sigma$ , are from the online compilation `tepcat`, and are rounded. Distinct measures for the same planet are demarcated by ‘/’. Spectrographs are C=CORALIE, H=HARPS, HD=HIDES, HN=HARPS-N, HR=HIRES, M=MIKE, S=SOPHIE, U=UCLES.

Planet	$\lambda$ ( $^{\circ}$ )	$\sigma$ ( $^{\circ}$ )	Instrument	Reference (respectively)
WASP-1 b	-79	4	S,H	Simpson et al. (2011c), see also Albrecht et al. (2011b)
WASP-2 b	-153	13	H,C	Triaud et al. (2010), see also Albrecht et al. (2011b)
WASP-3 b	15/3/5/20	9/3/6/3	S/HR/S/spots	Simpson et al. (2010b); Tripathi et al. (2010); Miller et al. (2010); Oshagh et al. (2013a)
WASP-4 b	4/-1	38/13	H,C/M	Triaud et al. (2010); Sanchis-Ojeda et al. (2011)
WASP-5 b	12	9	H,C	Triaud et al. (2010)
WASP-6 b	-11/7	16/4	H/spots	Gillon et al. (2009a); Tregloan-Reed et al. (2015)
WASP-7 b	86	6	M	Albrecht et al. (2012a)
WASP-8 b	-123/-143	4/2	H/H	Queloz et al. (2010); Bourrier et al. (2017a)
WASP-11 b	7	5	HN	Mancini et al. (2015a)
WASP-12 b	59	18	M	Albrecht et al. (2012a)
WASP-13 b	8	13	S	Brothwell et al. (2014)
WASP-14 b	-14/-33	17/7	HD,HR/S	Johnson et al. (2009a); Joshi et al. (2009)
WASP-15 b	-139	5	H,C	Triaud et al. (2010)
WASP-16 b	-4/11	12/23	C,H/M	Brown et al. (2012a); Albrecht et al. (2012a)
WASP-17 b	-148/-150/167/-149	5/49/11/8	H,C/H/M/H	Triaud et al. (2010); Anderson et al. (2010b); Bayliss et al. (2010); Anderson et al. (2011e)
WASP-18 b	4/13	5/7	H,C/M	Triaud et al. (2010); Albrecht et al. (2012a)
WASP-19 b	5/15/1	5/11/1	H/M/spots	Hellier et al. (2011a); Albrecht et al. (2012a); Tregloan-Reed et al. (2013)
WASP-20 b	8	4	C,H	Anderson et al. (2015a)
WASP-22 b	22	16	C,H	Anderson et al. (2011b)
WASP-23 b	[prograde]	-	H	Triaud et al. (2011)
WASP-24 b	-5/-6	4/4	S,H/H	Simpson et al. (2011c); Smith et al. (2012b)
WASP-25 b	15	7	C,H	Brown et al. (2012a)
WASP-26 b	-34	31	M	Albrecht et al. (2012a)
WASP-28 b	8/6	18/17	C,H	Anderson et al. (2015a); Močnik et al. (2017a)
WASP-30 b	-7	23	H	Triaud et al. (2013b)
WASP-31 b	3/6	3/6	C,H/M	Brown et al. (2012a); Albrecht et al. (2012a)
WASP-32 b	10/-2	6/18	C,H/S	Brown et al. (2012a); Brothwell et al. (2014)
WASP-33 b	252/-110/-113	0.7/0.5/0.2	various	Brothwell et al. (2014); Johnson et al. (2015a)
WASP-38 b	15/8	38/5	S,H/C,H	Simpson et al. (2011c); Brown et al. (2012a)
WASP-41 b	29/6	12/11	H/spots	Neveu-VanMalle et al. (2016); Southworth et al. (2016)
WASP-43 b	4	7	HN	Esposito et al. (2017)
WASP-47 b	0	24	HR	Sanchis-Ojeda et al. (2015b)
WASP-52 b	24/4	13/8	S/spots	Hébrard et al. (2013b); Mancini et al. (2017)
WASP-53 b	-1	12	H	Triaud et al. (2017b)
WASP-61 b	4	18	H	Brown et al. (2017a)
WASP-62 b	19	5	H	Brown et al. (2017a)
WASP-66 b	-4	22	U	Addison et al. (2016)
WASP-69 b	0	2	HN	Casasayas-Barris et al. (2017)
WASP-71 b	20/-2	10/7	S/H	Smith et al. (2013); Brown et al. (2017a)
WASP-76 b	[misaligned]	-	H	Brown et al. (2017a)
WASP-78 b	-6	6	H	Brown et al. (2017a)
WASP-79 b	-106/-95	16/1	U/H	Addison et al. (2013); Brown et al. (2017a)
WASP-80 b	75/-14	4/14	C,H/H	Triaud et al. (2013a, 2015)
WASP-84 b	0	2	C,H	Anderson et al. (2015a)
WASP-85 b	0	14	spots	Močnik et al. (2016b)
WASP-87 b	-8	11	U	Addison et al. (2016)
WASP-94A b	151	20	C	Neveu-VanMalle et al. (2014)
WASP-103 b	3	33	U	Addison et al. (2016)
WASP-107 b	$\psi = 90 \pm 50$	-	Kepler/K2	Dai & Winn (2017)
WASP-111 b	-5	16	C	Anderson et al. (2014a)
WASP-117 b	44	11	C,H	Lendl et al. (2014)
WASP-121 b	-257	5	C	Delrez et al. (2016)
WASP-152 b	2	9	S,HN	Santerne et al. (2016a)
WASP-167 b	-165	5	H	Temple et al. (2017)

Systems measured to date include examples of well-aligned systems, such as WASP-3 (Miller et al., 2010; Tripathi et al., 2010; Simpson et al., 2010b), and the bright hot Jupiters HD 189733 (Winn et al., 2006b; Triaud et al., 2009; Collier Cameron et al., 2010a; Cegla et al., 2016a) and HD 209458 (Queloz et al., 2000a; Winn et al.,

2005; Albrecht et al., 2012b). There are numerous misaligned systems such as XO-3 (Hébrard et al., 2008), and the bright radial-velocity discovered transiting systems HD 149026, HD 17156, and HD 80606.

There are also retrograde orbits, e.g. HAT-P-7 (Winn et al., 2009d; Narita et al., 2009b; Triaud et al., 2010);

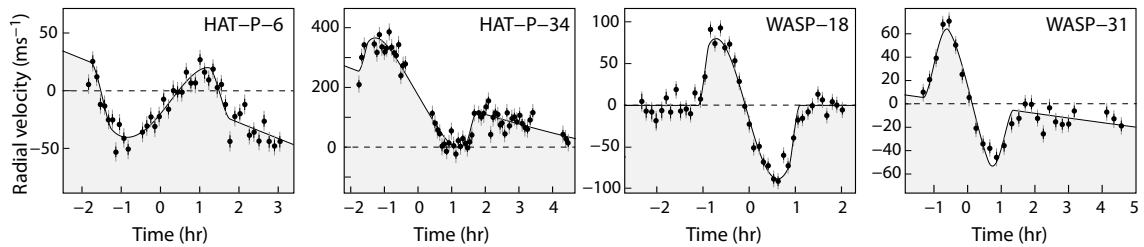


Figure 6.72: Rossiter–McLaughlin profiles for four transiting exoplanets observed with Magellan South (Clay) equipped with the Planet Finder Spectrograph (PFS, Crane et al., 2010), showing the best-fit radial velocities around transit. Black error bars indicate the internal radial velocity uncertainties; the grey bars also include stellar jitter. From Albrecht et al. (2012b, Figures 3, 5, 11, 14), by permission of IOP Publishing/AAS.

multi-transiting systems, e.g. Kepler–30 (Sanchis-Ojeda et al., 2012); hot Neptunes, e.g. HAT–P–11 b (Winn et al., 2010c; Hirano et al., 2011b); and a circumbinary, Kepler–16A b, in which the primary’s rotation, and stellar and planetary orbits, are all aligned (Doyle et al., 2011).

**Bimodal distribution** Studies have shown that there is a bimodal distribution of spin–orbit angles (e.g. Fabrycky & Winn, 2009; Marchi et al., 2009; Triaud et al., 2010), with a fraction of systems being well aligned, while the others have random (isotropic) mutual orientations (cf. Figure 6.73), suggesting that there are multiple mechanisms populating close-in planets (§6.18.8).

**Retrograde orbits** The existence of retrograde orbits, in which the planet’s component of orbital angular momentum is counter to that of the stellar rotation, had been predicted by planet–planet scattering or Lidov–Kozai migration models. The possibility of chaotic transitions of a solar system planet under tidal interactions (Beletskii et al., 1996; Laskar, 2003) has been extended to the influence of tidal and magnetic perturbations for short-period exoplanets by Gusev & Kitiashvili (2006).

Observations of HAT–P–7 by Winn et al. (2009d) were the first to reveal a polar or possibly retrograde orbit. Its retrograde nature, with  $\lambda \approx -132^\circ$ , was confirmed by Narita et al. (2009b). Other examples of such highly perturbed orbits have since been found.

Hébrard et al. (2011a) noted an apparent obliquity trend in the form of a mass cut-off for retrograde planets: all 7 known retrograde planets at the time were hot Jupiters with  $M_p < 3M_J$  (some 60% of the planets in the same mass range being prograde and approximately aligned), while most of the more massive planets ( $M_p > 4M_J$ ) were prograde, but misaligned.

**Circumbinary systems** The first circumbinary system in which the Rossiter–McLaughlin effect was measured was Kepler–16(AB) b. The stars (0.7 and  $0.2M_\odot$ ) are in a 41-d eccentric orbit, and the planet ( $0.3M_J$ ) circles both every 229 d. The planes of the circumbinary and stellar orbits are aligned to within  $0.5^\circ$  (Doyle et al., 2011), already suggesting that all three bodies inherited their an-

gular momentum from a single disk, as opposed to dynamical scenarios that are often invoked for triple systems such as close encounters (Mikkola, 1984), or dynamical decay (Sterzik & Tokovinin, 2002).

Measurements during the primary transit, Kepler–16A, yield  $\lambda = -1.6 \pm 2.4^\circ$  (Winn et al., 2011a), indicating that the planet orbit is also aligned with the projected obliquity of the primary. The system’s angular momentum components (stellar orbit, planetary orbit, primary rotation, secondary rotation, and planetary rotation) have magnitudes in the ratios 10000:40:1:0.1:0.001, indicating that Kepler–16 is an orderly system with good alignment between at least the three largest angular momentum contributions. Kepler–16 was also the longest-period stellar binary for which a stellar obliquity has been measured (Albrecht et al., 2011a, Table 1).

**Multi-planet systems** There are only a small number of (projected) obliquity measurements in systems comprising multiple-transiting planets. On the assumption that all transiting planets in the system are co-planar, then measurement of  $\lambda$  for a single planet is taken to represent the alignment of the system as a whole.

The first for which the projected obliquity was measured was Kepler–30 b, based on the occurrence of star spots (Sanchis-Ojeda et al., 2012). Estimates for Kepler–50 b/c and Kepler–65 b/c/d have been made from asteroseismology (Chaplin et al., 2013). Measurements of the Rossiter–McLaughlin effect have been made for Kepler–89 d (Hirano et al., 2012a; Albrecht et al., 2013), Kepler–25 c (Albrecht et al., 2013), WASP–47 b (Sanchis-Ojeda et al., 2015b), and Kepler–9 b (Sanchis-Ojeda et al., 2015b). All are consistent with spin–orbit alignment.

**Host star dependence** Significantly fewer hot Jupiters are known transiting hot stars,  $T_{\text{eff}} \geq 6700$  K (Temple et al., 2017), in part a selection effect given that planets transiting hot or fast-rotators are harder to validate. There is also a dearth of hot Jupiters orbiting very fast rotators, in which the star rotates faster than the planetary orbit (e.g. Wu & Murray, 2003; Fabrycky & Tremaine, 2007; McQuillan et al., 2013b). In such stars the tidal decay of a prograde hot Jupiter would be reversed.

From radial velocity measures (Winn et al., 2010a, 2011b; Albrecht et al., 2012b), and line-of-sight stellar rotation velocities (Schlaufman, 2010), misaligned systems are found to be associated with hotter stars ( $T_{\text{eff}} \geq 6250$  K, or  $M_{\star} \geq 1.2M_{\odot}$ ). For  $M_{\star} > 1.2M_{\odot}$ , those older than 2–2.5 Gyr, when stars develop a significant convective envelope (Triaud et al., 2013a), are aligned.

Results from the study of Dai & Winn (2017) are shown in Figure 6.73, in which all reliable obliquities (based on the Rossiter–McLaughlin effect, spot modeling, or asteroseismology) are shown as a function of  $M_p/M_{\star}$  and  $q/R_{\star}$ , where  $q = a(1 - e)$  is the pericentre distance. The size of each data point encodes the confidence in each system's departure from alignment; the largest points are definitely misaligned. For hot stars, the chance of being significantly misaligned does not depend on either  $M_p/M_{\star}$  or  $q/R_{\star}$ , while for cool stars, misaligned systems are all in the region  $q/R_{\star} \geq 8$ .

Similar effects are seen in obliquities derived statistically from star spots in photometric time series (§6.14.2).

### 6.18.8 Implications for migration models

While many of the measured systems have small values of  $\lambda$ , a significant number are highly misaligned (Figure 6.73). The earliest results were interpreted as providing evidence for two distinct mechanisms for inserting hot Jupiters into their close-in orbits. In the first, type II migration, disk–planet tidal interactions cause the planet to migrate inwards, largely preserving their initial spin–orbit alignment. In the second, some close-in giant planets may have arrived at their current locations through gravitational perturbations from other massive bodies, e.g. in mutually inclined binary systems (Wu et al., 2007), in either case followed by tidal dissipation and circularisation.

Another cause of a large  $\lambda$  may be misalignment between the stellar rotation and its protoplanetary disk (Bate et al., 2010a; Lai et al., 2011). Other processes which may adjust orbits after formation are discussed in §12.4. For Earth-mass planets, the giant impact stage of protoplanetary collisions is presumed to determine their initial spin state (e.g. Kokubo & Ida, 2007).

Observationally, Winn et al. (2010a) and Albrecht et al. (2012b) found evidence that the obliquities of many hot Jupiter systems have been affected by tidal evolution: the systems expected to undergo the strongest planet–star tidal interactions were found to have preferentially low obliquities, while systems with weaker tides have a more random distribution. This suggests that at the time of hot-Jupiter formation, before tides had any opportunity to act, the orbital planes were only loosely correlated with the equatorial planes of their host stars. This in turn suggests that whatever process produces hot Jupiters also causes their orbits to be tilted away from the initial plane of formation, favouring

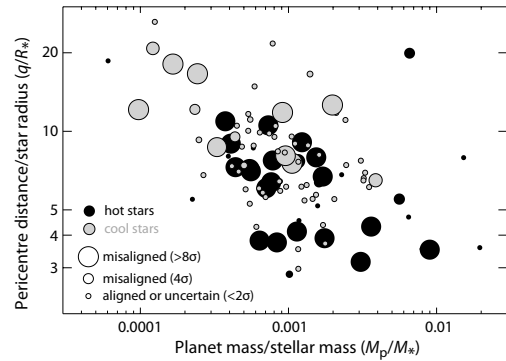


Figure 6.73: Stellar obliquity as a function of  $q/R_{\star}$ , the pericentre distance in units of  $R_{\star}$ , versus  $M_p/M_{\star}$ . Solid circles are stars with  $T_{\text{eff}} > 6200$  K (generally  $> 1.2M_{\odot}$ ) and grey circles are for cooler stars. The symbol size increases with  $n_{\sigma} = |\lambda|/\sigma_{\lambda}$ , the confidence with which a non-zero obliquity can be excluded (smallest have  $n_{\sigma} < 2$ , largest have  $n_{\sigma} > 8$ ). From Dai & Winn (2017, Figure 5), by permission of IOP Publishing/AAS.

disruptive scenarios such as planet–planet scattering or Lidov–Kozai oscillations as opposed to gradual inspiral within the protoplanetary disk.

There is also the possibility that high obliquities are a generic feature of planetary systems, not specific to hot-Jupiter migration. There are several proposed mechanisms for tilting a star relative to its protoplanetary disk: chaotic accretion (e.g. Bate et al., 2010a; Thies et al., 2011), magnetic star–disk interactions (Lai et al., 2011; Foucart & Lai, 2011), torques due to internal gravity waves (Rogers et al., 2012), and torques due to stellar fly-bys (Batygin, 2012). In these scenarios, high obliquities should be observed not only in hot-Jupiter systems but also in a broader class of planetary systems.

Any theory attempting to explain the occurrence of high obliquities must distinguish between hot and cool stars, and between wide- and close-orbiting planets around cool stars. Mechanisms that simply tilt the protoplanetary disk at an early stage, such as chaotic accretion or torques due to stellar fly-bys, do not have these properties (Xiang-Gruess, 2016; Dai & Winn, 2017).

**Theories of host star dependence** The observed obliquity trends (in terms of  $T_{\text{eff}}$  and  $M_{\star}$ ) have been taken to suggest that planet formation and migration are different for low- and high-mass stars, or that the subsequent tidal evolution is different, specifically due to different outer convection zones and consequently different rates of tidal dissipation (e.g. cool stars with thick convective envelopes facilitating realignment), or that other internal mass-dependent transport processes are at work. Various models have been put forward (Winn et al., 2010a; Morton & Johnson, 2011a; Albrecht et al., 2012b; Hansen, 2012; Lai, 2012; Rogers et al., 2012; Rogers & Lin, 2013; Smith et al., 2013; Valsecchi & Rasio, 2014b; Xue et al., 2014; Matsakos & Königl, 2015).

Hot Jupiters may also influence the outer layers of hot stars, and their thinner convective envelopes may be easier to ‘realign’ if they are only weakly coupled to the interior, as suggested for the hot tidally-synchronised  $\tau$  Boo (Catala et al., 2007). The other observed obliquity trend, a mass cut-off for retrograde planets (Hébrard et al., 2011a), also suggests that hot stars are tidally influenced by their associated hot Jupiter.

Dawson (2014) linked the temperature cut-off to the onset of magnetic braking (§6.29.5), rather than to tidal dissipation efficiency, or whether the star’s convective envelope is tidally realigned independently of the interior. A model based on equilibrium tides (§10.11.6), combined with magnetic braking, and a small effective stellar moment of inertia ( $I_{\star, \text{eff}}$ ) participating in the tidal realignment then leads to different time scales for orbital decay, spin–orbit alignment, and retrograde ‘flipping’, producing the various observed trends.

Specifically, for cool stars, strong magnetic braking slows the rotation, allowing the planet to realign the star’s outer layer without synchronisation. Both hot and cool stars require an effective moment of inertia some 30–100 times lower than the stellar total. For cool stars, magnetic braking shrinks the spin amplitude without changing its direction, so that a small  $I_{\star, \text{eff}}$  allows minimal orbit decay to ‘nudge’ the star into realignment. For hot stars, a small  $I_{\star, \text{eff}}$  allows massive planets to flip from retrograde to prograde, producing the observed retrograde planetary mass cut-off. More massive planets partially overcome magnetic braking to spin up the star, leading to an observed planet-mass-stratification of host star rotation frequency for cool stars.

**Multi-transiting systems** In the five multi-transiting systems measured by Albrecht et al. (2013), obliquities are consistent with spin–orbit alignment. In such systems, the planet orbits are likely to be co-planar, and presumably mark the plane of the protoplanetary disk out of which the planets formed. If these systems generally have low stellar obliquities, then the high obliquities in hot-Jupiter systems are probably due to planet migration. If, instead, the obliquity distributions of multi-transiting systems and hot-Jupiters are similar, then the obliquities are clues to more general processes in star and planet formation, and not specific to hot Jupiters. The present results on multi-planet systems favours the former. This alignment is unlikely to be the result of tidal interactions because of their relatively large orbital distances and low planetary masses, and suggests that the planets in multiple-planet systems might have migrated via disk–planet interactions.

In contrast, hot-Jupiter host stars commonly have large spin–orbit misalignments whenever tidal interactions are weak. In particular, the weak-tide subset of hot-Jupiter host stars includes high obliquities in a distribution which is consistent with isotropic (Albrecht et al., 2013). The results for multi-planet systems therefore support the idea that the inward migration of close-in gas-giants is fundamentally different from the migration occurring in compact multiple-planet systems. The evolutionary path of hot Jupiters not only brought them close to their host stars, but also transported them out of the orbital plane of the disk in which they formed.

## 6.19 Secular timing effects

To first order, a transiting planet would be expected to have a constant orbital period. However, various effects may lead to changes in the interval between successive transits, in the transit duration, in the interval between transits and the secondary eclipse, and in the form of the light curve including differences in the ingress and egress shapes and times.

Such transit time variations include perturbations due to other gravitating bodies, tidal forces, and relativistic precession, as well as apparent effects due to changes in geometrical projection (proper motion and parallax) as viewed by the observer. Transit timing variations and transit duration variations due to effects in multi-planet systems are considered in Section 6.20.

### 6.19.1 Parallax and space motion

The timing and duration of a transit has a periodic dependency on the observer’s position due to trigonometric parallax, and an apparent secular evolution due to the star’s space motion (Figure 6.74); both effects have been considered by Scharf (2007) and Rafikov (2009b).

For an orbit co-planar with the Earth–Sun system, observers at two extremes of Earth’s orbit would register an alignment phenomenon displaced in time by

$$\Delta t = \frac{A_m P}{\pi d_{\star}}, \quad (6.121)$$

where  $A_m$  is the mean orbital radius of the Earth (1 au),  $P$  the orbital period, and  $d_{\star}$  the distance to the star. For  $P = 400$  d and  $d_{\star} = 10$  pc,  $\Delta t \approx 5$  sec; the effect decreases linearly with increasing  $d_{\star}$  and decreasing  $P$ , and so should be irrelevant for hot Jupiters. For different alignment geometries, the observer’s orbital motion results in a changing effective orbital inclination  $i$ , and hence a change in the apparent transit duration (Equation 6.9).

Changes in alignment due to the star’s proper motion,  $\mu$ , also leads to changes in measured transit time and transit duration (Rafikov, 2009b, eqn 11). For the co-planar alignment geometry, with  $d_{\star} = 100$  pc,  $P = 400$  d, and  $\mu$  corresponding to a transverse stellar velocity of  $20 \text{ km s}^{-1}$ , the secular change in transit time is 10 s over 10 yr. For an orthogonal alignment corresponding to a drift in the system’s apparent orbital inclination, the effect reaches 20–200 s (Scharf, 2007).

In multi-site observations of WASP-12 b, Maciejewski et al. (2013a) noted that the effects are too small to be observed at present. Ofir (2014b) estimated that 200 transiting systems have timing effects greater than 1 s, and that the effect will be observable with PLATO.

**Shklovskii effect** Rafikov (2009b) gives an expression for the analogue of the *Shklovskii effect* in pulsar timing (Shklovskii, 1970) due to the special relativistic contribution to the orbital period arising from a combination of the star’s radial motion and the finite velocity of light. For large systemic radial velocities, this may be comparable to general relativistic precession.

### 6.19.2 Distant stellar or planetary companions

Interactions with a distant stellar or planetary companion on a wide orbit will result in a long-period transit time variation through the light-travel-time effect. Assuming a stellar binary frequency for hot Jupiter host stars equal to that determined in the solar neighbourhood as a whole, and that the planetary and binary orbits are co-planar, Montalto (2010) estimated that 1.0% will have a probability > 99% to present transit timing variations > 50 s induced by stellar binarity after 5 yr of observation, and 2.8% after 10 yr. Montalto et al. (2012) used the condition to exclude companions to WASP-3 b with  $M_p \gtrsim 100M_\oplus$  and  $P \lesssim 10P_b$ .

### 6.19.3 General relativistic effects

Iorio (2011a) derived general relativistic corrections to the transit duration, radial velocity, time between primary and secondary eclipses, and the interval between successive transits. Dynamical effects considered are the centrifugal oblateness of star and planet, their mutual tidal bulges, and effects of a distant third-body.

In terms of the transit period, for example, all effects give rise to long-term variations, non-zero even for circular orbits. Effects due to stellar and planetary oblateness, the gravitomagnetic field, and a third-body are harmonic, while those induced by tidal bulges and the gravitoelectric field are secular.<sup>4</sup>

The largest effect, of order  $10^{-6}$ , is due to the gravitoelectric (Schwarzschild-like) general relativistic correction. Smaller effects are due to the planet's tidal bulge ( $8 \times 10^{-7}$ ), the star's tidal bulge ( $10^{-8}$ ), planet oblateness ( $1 \times 10^{-7}$ ), stellar oblateness ( $8 \times 10^{-9}$ ), and gravitomagnetic effect ( $\sim 10^{-10}$ ). The effect of a distant Jupiter-like planet at 0.1–1 au is  $10^{-5} - 10^{-8}$ , while an Earth-type planet at the same distances is  $10^{-8} - 10^{-11}$ .

These may be compared with a suggested detectable change in transit period of  $\sim 10^{-12} - 10^{-13}$  over 10 yr.

**Higher-order effects** Tests of general relativity through a parameterised post-Newtonian formalism, targeting an accuracy of 6% for a planet with  $P = 1$  d and  $e = 0.1$ , would require accuracies in transit timing of  $\sim 1 \text{ s yr}^{-1}$  (Zhao & Xie, 2013). Comparable effects were found by Yamada & Asada (2012), and quantified for 6 systems (including GJ 436 and XO-3) by Li (2012b).

Effects of a Yukawa-type correction to an inverse square law of gravity are, in extreme cases, at levels of  $\sim 0.1 \text{ s yr}^{-1}$  (Xie

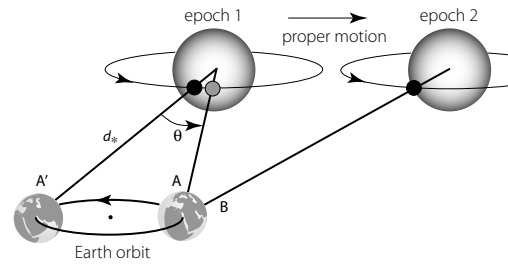


Figure 6.74: From different points in Earth's annual orbit around the Sun (AA') the observer registers a different time for a given contact due to parallax. As a distinct effect, the star's proper motion through space leads to a change in the exoplanet's projected orbital plane viewed by the observer (AB), leading to a secular change in the measured transit times.

& Deng, 2014). Assessments have also been made for a Hořava–Lifshitz (quantum) gravity (Iorio & Ruggiero, 2010). Tests of modified gravity via deviations from Kepler's third law were considered by Vargas dos Santos & Mota (2017).

**Variation of the fundamental constants** Long-term monitoring of transiting systems puts limits on their  $\dot{P}(t)$ , which can be translated into constraints on the variation of the gravitational constant,  $\dot{G}$  (e.g. Li, 2012a). For the 10 highest signal-to-noise Kepler systems with no evidence for transit timing variations (including TrES-2, HAT-P-7, HAT-P-11, Kepler-5, Kepler-6, Kepler-7), Masuda & Suto (2016) derived the limit  $\dot{G}/G \leq 10^{-6} \text{ yr}^{-1}$  assuming constant  $\dot{G}$ . While less stringent by a factor  $10^6$  than those based on pulsar timing (e.g. Zhu et al., 2015c) or lunar laser ranging (e.g. Hofmann et al., 2010), the limit can be improved with more systems over a longer time interval. Similar tests for variations of the velocity of light,  $c$ , have been considered (Mushailov & Teplitskaya, 2012).

### 6.19.4 Apsidal precession

Spherical masses obey a  $r^{-2}$  force law, and consequently execute closed elliptical orbits. In practice, the centrifugal potential of spinning bodies causes rotational flattening, while the tidal potential of a nearby mass raises tidal bulges. Both create gravitational quadrupole fields, with an  $r^{-3}$  dependency, that result in orbit precession. Other orbiting planets, and the spacetime metric of general relativity, also result in precessional motion.

Observational consequences for the planet orbit can be split into two components: *apsidal precession* in which the orbit ellipse rotates in its own plane, and *nodal precession*, out of the orbit plane, in which the orbit normal precesses about the total angular momentum vector. For eccentric orbits, both will result in long-term variations of the transit times (§6.20), and of the transit durations (§6.20.10). Miralda-Escudé (2002) and Ragozzine & Wolf (2009) derived expressions for various combinations of these effects. Typically, apsidal precession dominates (although see §6.19.5).

**Total apsidal precession** Apsidal precession refers to the rotation of the orbit's line of apsides (i.e., its major

<sup>4</sup> In its slow-motion weak-field approximation, general relativity predicts that slowly rotating bodies induce two types of perturbation on the orbital motion of a test particle. In the gravitoelectromagnetism formalism (GEM, e.g. Mashhoon, 2003), the largest *gravitoelectric* component depends only on its mass, and is responsible for the 'anomalous' secular precession of the perihelion of Mercury due to the Sun, of  $0.4298 \text{ arcsec yr}^{-1}$ . A smaller *gravitomagnetic* perturbation depends on its angular momentum, and causes the Lense–Thirring precession of the node and pericentre (Lense & Thirring, 1918).

axis). Also referred to as ‘periastron precession’ (but see footnote, page 17), it corresponds to the first derivative of the argument of pericentre.

There are a variety of physical effects which can generate significant apsidal precession, notably general relativistic effects, stellar quadrupole moment (due to the stellar oblateness), star–planet tidal deformations, and perturbations from other planets. Typically, but not always, apsidal precession is small.

Irrespective of the cause, contributions add linearly to first order. The total apsidal precession from various effects can therefore be written

$$\dot{\omega}_{\text{tot}} = \dot{\omega}_{\text{tid,p}} + \dot{\omega}_{\text{gr}} + \dot{\omega}_{\text{rot,p}} + \dot{\omega}_{\text{rot},\star} + \dot{\omega}_{\text{tid},\star} + \dot{\omega}_{\text{p2}}, \quad (6.122)$$

with the terms broadly in order of importance for an isolated hot Jupiter (Ragozzine & Wolf, 2009, eqn 13). The final term accounts for the effects of other planets.

In the solar system, Mercury’s perihelion precession is dominated by the other planets ( $5.32 \text{ arcsec yr}^{-1}$ ), with general relativistic effects of  $0.4298 \pm 0.0004 \text{ arcsec yr}^{-1}$ . The solar quadrupole moment adds a further  $0.00025 \text{ arcsec yr}^{-1}$  (Clemence, 1947; Iorio, 2005; Park et al., 2017).

**Tidal contribution**  $\dot{\omega}_{\text{tid},\star}, \dot{\omega}_{\text{tid,p}}$  are precession rates due to the tidal potentials of the star and planet, given by (Ragozzine & Wolf, 2009, eqn 6–7)

$$\dot{\omega}_{\text{tid},\star} \approx \frac{15}{2} k_{2\star} \left( \frac{R_{\star}}{a} \right)^5 \frac{M_{\text{p}}}{M_{\star}} \left( 1 + \frac{13}{2} e^2 + \dots \right) n \quad (6.123)$$

for the star, and analogously for the planet.  $k_2$  is the Love number (box, page 258). Using Jupiter and solar values for the planet and star, their ratio is

$$\frac{\dot{\omega}_{\text{tid,p}}}{\dot{\omega}_{\text{tid},\star}} = \frac{k_{2\text{p}}}{k_{2\star}} \left( \frac{R_{\text{p}}}{R_{\star}} \right)^5 \left( \frac{M_{\star}}{M_{\text{p}}} \right)^2 \approx 100, \quad (6.124)$$

assuming  $k_{2\text{p}}/k_{2\star} \approx 10$ . In consequence, the star raises a significant tidal bulge on the planet, which dominates the total precession (Equation 6.122).

For short period (hot Jupiter) planets, the planet’s proximity to the host star raises substantial tidal bulges, resulting in a significantly aspherical planetary gravitational potential, and thereby inducing significant apsidal precession. Accordingly, apsidal precession for hot Jupiters is expected to be primarily determined by the contribution from the planetary tidal bulge which, for small  $e$ , can be written (Ragozzine & Wolf, 2009, eqn 14)

$$\dot{\omega}_{\text{tid,p}} \approx 0.59 \left( \frac{k_{2\text{p}}}{0.3} \right) \left( \frac{M_{\star}}{M_{\odot}} \right)^{3/2} \left( \frac{M_{\text{p}}}{M_{\text{J}}} \right)^{-1} \left( \frac{R_{\text{p}}}{R_{\text{J}}} \right)^5 \times \left( \frac{a}{0.025 \text{ au}} \right)^{-13/2} \text{ degrees yr}^{-1}. \quad (6.125)$$

Ragozzine & Wolf (2009) predicted particularly large apsidal precession periods (dominated by the planetary

**Rotation,  $J_2$ , and Love numbers:** The rotation of stars and planets leads to a flattening of their polar regions. The resulting oblateness is quantified by the flattening parameter,  $f = (R_{\text{eq}} - R_{\text{pol}})/R_{\text{pol}}$ , where  $R_{\text{eq}}$  and  $R_{\text{pol}}$  are the equatorial and polar radii, which can (in principle) be determined empirically from imaging, or transit photometry (§6.14.7). They are related to the rotational period through contours of constant (gravitational and centrifugal) potential, expressed in terms of the spherical mass moments,  $J_n$ .

For the Sun, the quadrupole moment  $J_2 = (C - A)/M_{\odot} R_{\odot}^2$  (where  $C$  and  $A$  are the moments of inertia about the body’s rotation and equatorial axes respectively) results from the rotation of the stellar interior, and its mass distribution as a function of radius. Observations of the solar diameter indicate an oblateness ranging from  $8.8 \times 10^{-6}$  from stratospheric balloon observations (Lydon & Sofia, 1996),  $1.1 \times 10^{-5}$  measured from the ground (Bursa, 1986), and  $9.8 \times 10^{-6}$  from the MDI instrument on SOHO (Kuhn et al., 1998). The resulting difference in apparent diameter from equator to pole lies between 17–22 mas. Combined with a model of the solar interior and of the differential rotation constrained by helioseismology, these give model-dependent estimates of  $J_2 = (2.2 \pm 0.1) \times 10^{-7}$  (Mecheri et al., 2004). Empirical estimates of  $J_2 \sim 3 \times 10^{-6}$  are found from the effect of the solar quadrupole on lunar libration and the precession of planetary orbits.

In the solar system, oblateness reaches 0.098 for Saturn and 0.065 for Jupiter (Murray & Dermott, 2000).

A planet’s Love number,  $k_2$ , is the constant of proportionality between an applied second-degree potential, and the resulting field that it induces at the planet’s surface (e.g. Ragozzine & Wolf, 2009; Correia, 2014)

$$V_2^{\text{ind}}(R_{\text{p}}) \equiv k_{2\text{p}} V_2^{\text{app}}(R_{\text{p}}),$$

and is a measure of how the redistribution of mass caused by an external potential affects the external gravity field of the planet. It depends on the planet’s internal mass distribution, including the presence or absence of a solid core. For main sequence stars  $k_2 \approx 0.03$  (Claret, 1995) implies that their low-mass outer envelopes have little effect on the gravity field, while higher values for Saturn (0.32) and Jupiter (0.49) reflect their more uniform density distributions albeit with differing central condensation. Further details are given in Section 10.11.

tidal bulge, but including small contributions from general relativity and the star) for WASP–12 b, CoRoT–1 b, OGLE–TR–56 b, WASP–4 b, and TrES–3 b of around 18, 71, 116, 120, and 171 yr, respectively (their Table 1). These precession rates, of a few degrees per year, and up to  $19^{\circ}9 \text{ yr}^{-1}$  in the case of WASP–12 b, can be compared to a few degrees per century as the fastest general relativistic precession (Jordán & Bakos, 2008).

Observational confirmation is not straightforward because of their typically small orbital eccentricities (e.g. for WASP–12, Campo et al., 2011). Nevertheless its measurement, through its effect on the measured light curves, would directly probe the interior of the orbiting planet. Detailed studies for HAT–P–13 showed how improved measurement of the orbital eccentricity would place improved limits on  $k_{2\text{p}}$  and consequently

on the planetary core mass (Batygin et al., 2009a). Subsequently, Spitzer secondary eclipse observations have led to an improved orbit, to an estimate  $k_{2p} = 0.81 \pm 0.10$ , and a value consistent with models with low core mass, and possibly no solid core (Hardy et al., 2017), a result challenging core accretion models, at least in the absence of core erosion (§11.3.2).

Models which calculate oblateness for hot Jupiters assuming different core masses are given by, e.g., Barnes & Fortney (2003), and constraints on oblateness from transit light curves (but not the secular time evolution) have been determined by Carter & Winn (2010b).

**General relativistic contribution** General relativistic precession is given to first order by (e.g. Will, 1993)

$$\dot{\omega}_{\text{gr}} = \frac{3GM_{\star}n}{ac^2(1-e^2)}, \quad (6.126)$$

where  $n = 2\pi/P$  is the mean motion in  $\text{rad s}^{-1}$ . For  $P = 10 \text{ d}$ ,  $a \sim 0.1 \text{ au}$ , and  $e \approx 0$ ,  $\dot{\omega}_{\text{gr}} \approx 4 \times 10^{-7} n \approx 10^{-4} \text{ yr}^{-1}$ . The effect has been considered for exoplanets in some detail (Pál & Kocsis, 2008; Rafikov, 2009b), along with its specific observability for hot Jupiters (e.g. Iorio, 2006a; Adams & Laughlin, 2006b; Jordán & Bakos, 2008).

The components of  $\dot{\omega}_{\text{quad}}$  and  $\dot{\omega}_{\text{tide}}$  have  $a^{-2}$  and  $a^{-5}$  dependencies respectively, implying that, for long-period planets in single-planet systems, relativistic precession dominates. This imposes a lower limit on the total precession given by (Kane et al., 2012b, eqn 6)

$$\dot{\omega}_{\text{gr}} = \frac{0.0778}{(1-e^2)} \left(\frac{M_{\star}}{M_{\odot}}\right) \left(\frac{a}{0.05 \text{ au}}\right)^{-1} \left(\frac{P}{\text{d}}\right)^{-1} \text{ deg yr}^{-1}. \quad (6.127)$$

General relativistic apsidal precession rates are shown in Figure 6.76b. There are two distinct populations, with the divide occurring at  $10^{-3} \text{ deg yr}^{-1}$ , corresponding to the dearth of planets in the range  $a = 0.1 - 0.6 \text{ au}$  (Burkert & Ida, 2007; Cumming et al., 2008; Currie, 2009).

Equation 6.127 indicates that precession amplitudes are dominated by  $P$  rather than  $e$ . Thus, even planets in eccentric orbits do not exhibit significant relativistic precession at longer periods. Although total precession time scales are large (Miralda-Escudé, 2002; Jordán & Bakos, 2008), of greater observational relevance is the rate of change of the argument of pericentre.

**Other contributions**  $\dot{\omega}_{p2}$  is the precession rate due to a second planet, derived using the epicycle approximation for small  $e$  as (Miralda-Escudé, 2002, eqn 17)

$$\dot{\omega}_{p2} = \frac{3M_2 a^3}{4M_{\star} a_2^3} n. \quad (6.128)$$

For an Earth-like planet with  $M_2/M_{\star} \approx 3 \times 10^{-6}$ , and  $a_2 \approx 2a$ , the precession rate is  $\dot{\omega}_{p2} \approx 3 \times 10^{-7} n$ , comparable to that due to relativistic precession.

$\dot{\omega}_{\text{rot},\star}$  and  $\dot{\omega}_{\text{rot},p}$  are the precession rates due to the quadrupole field resulting from rotational flattening (e.g. Miralda-Escudé, 2002; Ragozzine & Wolf, 2009). For the star (Miralda-Escudé, 2002, eqn 16)

$$\dot{\omega}_{\text{rot},\star} = \frac{3J_2 R_{\star}^2}{2a^2} n. \quad (6.129)$$

For  $J_2 \approx 10^{-6}$  and  $R_{\star} \lesssim 0.1a$ ,  $\dot{\omega}_{\text{rot},\star} \lesssim 10^{-8} n$ , much smaller than  $\dot{\omega}_{\text{gr}}$ . For a hot Jupiter tidally locked and synchronously rotating with the star, spin periods are somewhat longer than that of Jupiter,  $\approx 10 \text{ h}$ . The rotational flattening scales with the inverse square of the spin period, with the consequence that  $\dot{\omega}_{\text{rot},p}$  is also small. The quadrupole term has been considered explicitly for HD 209458 (Iorio, 2006b).

### 6.19.5 Nodal precession

Nodal precession (see the introduction to Section 6.19.4) occurs when the orbit plane precesses around the total angular momentum vector, itself usually aligned with the rotation axis of the host star. Nodal precession is a consequence of a non-zero gravitational quadrupole field due to stellar oblateness. It also affects transit durations (§6.20.10).

The frequency of nodal precession is given by

$$\Omega = n \frac{R_{\star}^2}{a^2} \frac{3J_2}{4} \sin 2i, \quad (6.130)$$

where  $n = 2\pi/P$  is the orbital angular frequency,  $J_2$  is the quadrupole moment, and  $i$  is the orbit inclination relative to the stellar equatorial plane. Nodal precession can be the dominant precession term for polar orbits, while the dependence on  $n$  means that the effect is generally only relevant for short-period orbits.

The discovery of transiting hot Jupiters with almost polar orbits (§6.18) leads to the possibility of measuring transit time variations in such systems.

**Examples** Systems for which nodal precession has been assessed or determined include:

*Kepler-13Ab*: a hot Jupiter on an inclined orbit about a rapidly rotating star (§6.14.3). Szabó et al. (2012) measured a change of impact parameter  $db/dt = -0.016 \pm 0.004 \text{ yr}^{-1}$  from the changing transit duration.

*WASP-33b*: a fast rotating main sequence star hosts a hot Jupiter with  $a = 0.02 \text{ au}$  and  $e \sim 0$ , moving along a retrograde and almost polar orbit (Collier Cameron et al., 2010b; Herero et al., 2011). Classical and relativistic nodal precession rates were determined theoretically by Iorio (2011b). As a consequence of the close-in orbit and rapid stellar rotation, the quadrupole moment and angular momentum of the star are 1900 and 400 times larger than those of the Sun respectively, resulting in substantial classical and general relativistic non-Keplerian orbital effects. The resulting nodal precession rate is  $9 \times 10^9$  times larger than that induced by the Sun's oblateness on the orbit of Mercury, while the general relativistic gravitomagnetic nodal precession (footnote, page 257) is  $3 \times 10^5$  times

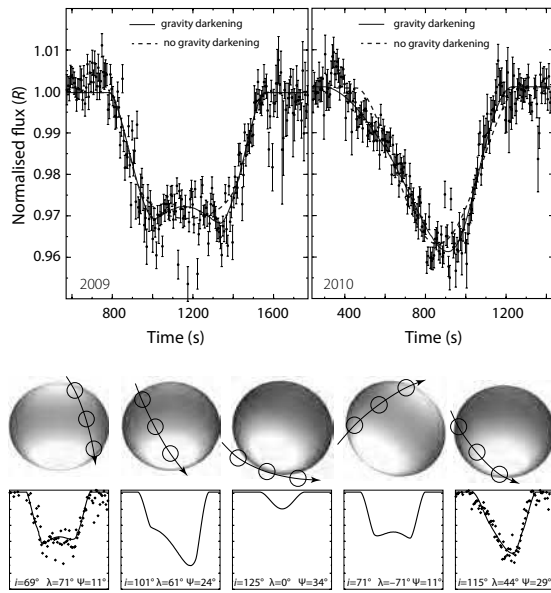


Figure 6.75: Light curves of PTFO 8–8695 b (CVSO 30) from the Palomar Transient Factory Orion project, from 2009 (left) and 2010 (right). Models of gravity darkening due to a fast-spinning host star fit at each epoch, but with very different orbit parameters. Models in which both stellar spin axis and planetary orbit normal precess can fit both epochs (here for  $M_{\star} = 0.34M_{\odot}$ ), giving predictions of the geometry and light curves at intermediate epochs (lower panels) including, centre, an almost complete disappearance of transits. From Barnes et al. (2013a, Figures 1, 2 and 8), by permission of IOP Publishing/AAS.

larger than the Lense–Thirring effect on Mercury due to the Sun’s rotation. The resulting changes in the transit duration are  $\sim 3 \times 10^{-6}$ ,  $2 \times 10^{-7}$ , and  $8 \times 10^{-9}$  for the stellar  $J_2$ , the planet’s rotational oblateness, and general relativistic components, respectively, suggesting that the effects may be measurable over several years (Iorio, 2011b).

Orbit changes over 6 yr were determined from line-profile tomography (§6.18.6, Johnson et al., 2015a). The changes in impact parameter ( $db/dt = -0.023 \pm 0.003 \text{ yr}^{-1}$ ) and in spin–orbit misalignment ( $d\lambda/dt = -0.49 \pm 0.08 \text{ deg yr}^{-1}$ ) gives a nodal precession  $d\Omega/dt = 0.37 \pm 0.05 \text{ deg yr}^{-1}$ , and limits on the stellar quadrupole moment of  $0.0054 \leq J_2 \leq 0.035$ .

**PTFO 8-8695 b:** a young hot Jupiter candidate ( $M_{\star} \sim 0.34M_{\odot}$ ,  $M_p \sim 3M_j$ ,  $P = 0.45 \text{ d}$ ; also known as PTFO–1 and CVSO 30), reported by van Eyken et al. (2012), but unconfirmed (Ciardi et al., 2015b). Transit profiles are of unusual shape, and distinctly different in the 2009 and 2010 observations, with the transit depth greater and its duration shorter in the latter. Detailed models by Barnes et al. (2013a) invoke gravity darkening due to a rapidly rotating star (§6.14.3) combined with precessional motion (Figure 6.75). Further literature is given in Appendix D.

In their model, both the stellar spin pole, and the planetary orbit normal (and the ascending node), precess around their mutual net orbital angular momentum vector. Compared to Earth’s precessional motion (box, page 260), this more complex behaviour arises from the comparable sizes of the stellar spin and planetary orbital angular momenta.

**Precession of the Earth:** Earth’s rotation axis precesses around the Earth–Sun plane every 26 000 yr, as a result of luni-solar torques acting on its rotational bulge. To first order, this maintains Earth’s obliquity (axis tilt), changing only the azimuthal direction in which the axis points [although variations in obliquity can arise due to interaction between the precessions of Earth’s spin and orbit resulting from torques from the other planets (Laskar et al., 1993; Lissauer et al., 2012a)]. Earth’s orbit is inclined by  $1^{\circ}57'$  to the solar system’s *invariable plane* (the plane normal to its net angular momentum vector,  $L_{\text{total}}$ ). Earth’s orbital angular momentum vector  $L_p$  precesses around  $L_{\text{total}}$  every 100 000 yr, although this is dominated by Jupiter’s gravity torque rather than the Sun’s rotational bulge.

Predictions about the future orbit and transit behaviour (Figure 6.75) suggest that there will be epochs where the transits disappear for months (i.e. when  $b > 1 + (R_p/R_{\star})$ ; cf. §6.14.14), as well as changing inclination (testable by radial velocity measures), changing stellar obliquity (with changing rotational line widths), changing stellar spectrum (i.e. different  $T_{\text{eff}}$  when pole-on or face-on), changing projected alignment (with  $\lambda$  varying between  $-80^{\circ}$  and  $+70^{\circ}$ , measurable through the Rossiter–McLaughlin effect), changing transit shape, and chromatic variations due to gravity darkening.

**Others:** others likely to show rapid nodal precession are CoRoT–11, OGLE–TR–9, and WASP–19 (Damiani & Lanza, 2011).

### 6.19.6 Tidal decay

In addition to the effects of apsidal precession due to tidal bulges, tidal effects in close-in planets lead to *tidal decay*, and a progressive shift in transit times (Sasselov, 2003). This tidal decay is also referred to as *orbit decay* or *tidal inspiraling*. The end result of this process is tidal disruption, disintegration, and engulfment (§6.14.21).

**Examples** Tidal decay, and its effect on transit times, has been considered explicitly for a number of systems.

**WASP–12:** with  $P = 1.08 \text{ d}$ , and observations over 4 yr, Maciejewski et al. (2016a) favoured a model of orbit decay (over apsidal precession) with an implied change in orbit period of  $(-2.56 \pm 0.40) \times 10^{-2} \text{ s yr}^{-1}$ . Further analysis is given by Weinberg et al. (2017).

**WASP–18:** with  $P = 0.94 \text{ d}$ , transit time shifts of  $2.8 \text{ s yr}^{-1}$  were predicted by Hellier et al. (2009a), but revised up to  $35.6 \text{ s yr}^{-1}$  by Birkby et al. (2014). With observations spanning 9 yr, Wilkins et al. (2017) found no evidence of such a rapid decay, concluding that  $Q'_{\star} \geq 1 \times 10^6$ , and thereby supporting the suggestion that F stars (with convective cores and thin convective envelopes) are significantly less tidally dissipative than solar-type stars (radiative cores and large convective envelopes).

**WTS–2:** in a 1.02-d orbit and close to its tidal destruction radius, shifts in transit times due to tidal decay of  $1.1 \text{ s yr}^{-1}$  were predicted, assuming  $Q'_{\star} = 10^6$  (Birkby et al., 2014).

### 6.19.7 Other time-dependent effects

Other time-dependent effects may arise from quasi-periodic variations in the quadrupole moment of magnetically active stars (the *Applegate mechanism*, box,



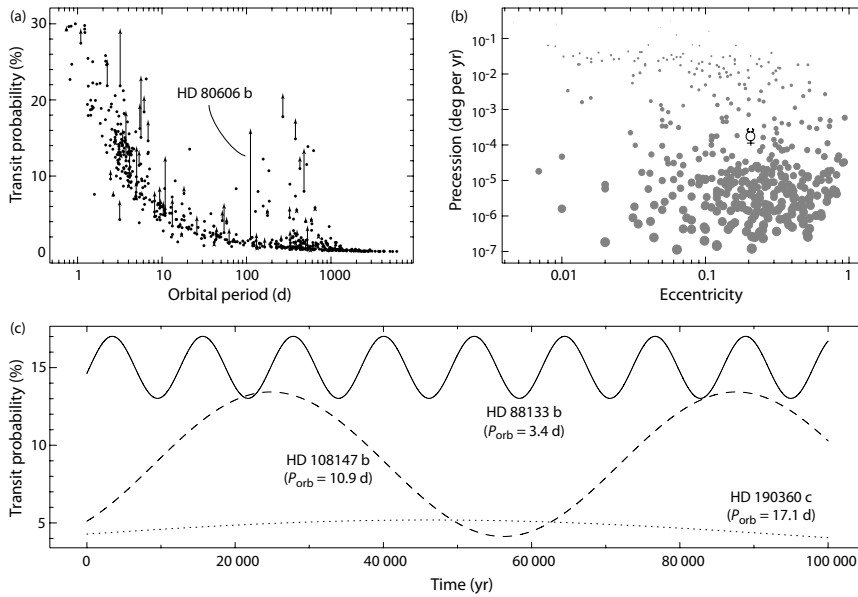


Figure 6.76: Transit probabilities and apsidal precession for the systems studied by Kane et al. (2012b): (a) transit probabilities as a function of orbital period. Vertical arrows indicate systems where a change in  $\omega$  from its current value, to  $\omega = 90^\circ$ , would result in a transit probability improvement of more than 1%. Planets with relatively high transit probabilities between 100–1000 d are due to giant host stars whose large radii dominates the probabilities (Equation 6.37); (b) general relativistic apsidal (or ‘periastron’) precession rates as a function of  $e$  for exoplanets with Keplerian orbit solutions. Circle sizes are (logarithmically) proportional to orbital period. The position of Mercury is indicated; (c) cyclic transit probabilities resulting from general relativistic apsidal precession for three known exoplanets: HD 88133 b, HD 108147 b, and HD 190360 c. This is shown from the present epoch and projected forward 100 000 yr. From Kane et al. (2012b, Figures 1, 2 and 4), by permission of IOP Publishing/AAS.

page 114; Applegate, 1992), assessed in the context of WASP-18, and which may be expected to reach a few seconds over 10 yr (Watson & Marsh, 2010); the effects of *magnetic breaking* (Lee et al., 2009; Barker & Ogilvie, 2009); and the ‘non-gravitational’ *Yarkovsky effect* (Botke et al., 2006), due to the anisotropic emission of thermal photons by a rotating body (Fabrycky, 2008).

### 6.19.8 Transitional transits

Single transiting planets orbiting single stars will generally transit at every inferior conjunction. However, there are various circumstances where transits, as viewed from any given location, will not necessarily continue indefinitely. For example, transits may disappear as a consequence of secular orbit precession (Agol et al., 2005, Section 9.2), and in particular in the case of currently grazing transits (Section 6.14.14), or may cease and start again (on time scales of years or decades or more) in more complex dynamical configurations such as circumbinary systems.

This phenomenon, referred to here as that of *transitional transits*, can occur under various circumstances.

**Rotationally-deformed star** Close-in planets occupying an inclined orbit around a rotationally deformed star are susceptible to nodal precession which may lead to such transitional

transits. For the rapidly rotating stellar host PTFO 8–8695 (CVSO 30), for example, along with a variety of complex effects (§6.19.5), the disappearances over time scales of months has been predicted (Barnes et al., 2013a).

**Circumbinary planets** For circumbinary planets, effects can be considerably more pronounced, with the consequence that even for eclipsing binary systems, generally considered to be well-suited candidates for the discovery of transiting planets due to the favourable orbital orientation, misaligned orbits may result in intermittent transits or long gaps (Schneider, 1994a; Kipping & Lam, 2017; Martin, 2017a,b). Further details, and examples, are given in Section 6.31.

**Transitability** Elaborating on earlier studies (Schneider, 1994a; Welsh et al., 2012; Kratter & Shannon, 2014), Martin & Triaud (2014) introduced the related concept of *transitability* to describe an orbital configuration (characterised by their mutual inclination,  $\Delta i$ , and mutual longitude of the ascending nodes,  $\Delta\Omega$ ) where the planet and binary orbits intersect on the sky. In this scenario transits are possible but not guaranteed on every passage of the planet past the binary, because of the relative motion of the three bodies. The probability of transitability is higher than for a single star, and is an increasing function of the mutual orbit inclination (Martin & Triaud, 2015). For example, a circumbinary planet at 1 au around a 0.3 au eclipsing binary will eventually transit if  $\Delta i > 0.6^\circ$ .

**Tight transits** A related phenomenon is that circumbinary planets can transit the same star more than once during a single planetary orbit, a phenomenon referred to as *tight transits* by Liu et al. (2014b), and discussed further in Section 6.31.

**Apsidal and nodal precession** Only a relatively small fraction of the known exoplanets discovered from radial velocity measurements are known to transit their host. However, the transit probability of short period and eccentric orbits can have a reasonable time dependence due to the effects of apsidal and nodal precession (§6.19.4), thus altering their transit potential and predicted transit time. Kane et al. (2012b) investigated the magnitude of these precession effects on transit probabilities and applied this to the known radial velocity exoplanets. They focused on planets not currently known to transit, particularly long-period eccentric planets. They investigated the subsequent rate of change of the transit probability to show how they drift in and out of a transiting orientation.

Planets in eccentric orbits are of particular interest because of their enhanced transit probabilities (Kane & von Braun, 2008, 2009). Their eccentricity also subjects them to orbit precession, with implications for transit times and transit durations (Carter & Winn, 2010a; Damiani & Lanza, 2011; Heyl & Gladman, 2007; Jordán & Bakos, 2008; Miralda-Escudé, 2002; Pál & Kocsis, 2008; Ragozzine & Wolf, 2009).

One consequence of such precession is that a planet that exhibits transits now may not do so at a different epoch, and *vice versa*. This has been specifically noted in the case of GJ 876 c, for example, which does not currently transit, but may do so in the relatively near future (Laughlin et al., 2005a).

**Cyclic transits** Since the transit probability for any given planet with  $e \neq 0$  is a function of  $\omega$  (Equation 6.37), apsidal precession leads to a cyclic change in transit probability. Kane et al. (2012b) tabulate results for 60 non-transiting systems with  $e \neq 0$ , and give the apsidal precession rate, transit probability, maximum transit probability for  $\omega = 90^\circ$ , time from the current epoch until maximum transit probability, and the rate of change of transit probability.

Figure 6.76c shows this time dependence over  $10^5$  yr for three systems: HD 88133 b, HD 108147 b, and HD 190360 c (with orbital periods of 3.4, 10.9, and 17.1 d respectively). HD 108147 b shows very large amplitude variations due to its high eccentricity,  $e = 0.53$ . HD 190360 c has a smaller  $e$  and  $\dot{\omega}_{GR}$ , leading to a cyclic time scale  $\gg 10^5$  yr.

Although, for all systems considered, the time required to reach maximum transit probability is beyond the time scales of immediate observational interest, the rate of change provides an indication of which planets may have a measurable change in configuration. Even for HD 156846 b (Kane et al., 2011d), with one of the longest  $P$  and one of the highest  $e$ , detection of apsidal precession is unlikely. In contrast, the hot Saturn HD 88133 b (Fischer et al., 2005) has the highest transit probability rate of change, at around  $10^{-5} \text{ yr}^{-1}$ , and a precession rate that will cause a shift of  $\Delta\omega \sim 0.03^\circ \text{ yr}^{-1}$ .

Uncertainties on  $\omega$  have a mean of  $28^\circ$  and a median of  $15^\circ$  for their overall sample, much higher than the estimated precession effects. Uncertainties on  $\omega$  of less than one degree are not unusual, especially for planets with high  $e$ , with the current uncertainty on  $\omega$  for HD 156846 b of only  $0.16^\circ$  (Kane et al., 2011d). Various orbit refinement programs are ongoing (e.g. Kane et al., 2009), which should result in the detection of a number of these effects in a reasonable time.

Kepler planets may show significant apsidal precession due to perturbations from other planets, perhaps leading to an eventual transit from currently non-transiting planets. For example, Kepler-19 c is inferred from transit time variations of the inner planet, but does not currently transit.

## 6.20 Transit timing variations

### 6.20.1 General considerations

Transits of a single planet on a Keplerian orbit occur at regular times given by the orbital period. With a further body in the system (a stellar companion, another planet, or an accompanying satellite) the orbit is no longer Keplerian, and the transits are no longer strictly periodic.

*Transit timing variations* (TTVs) describe the deviations from the linear ephemeris of a strictly Keplerian orbit. They may be dominated by gravitational interactions of a transiting planet with a third body, which may itself be transiting or not. They may also occur in multi-planet systems with negligible planet–planet interactions but where the host star is itself moving in a significant orbit around the system barycentre.

**Dynamical diagnostics** High-accuracy transit times can provide relatively robust evidence for deviations from a constant-period Keplerian orbit (Agol et al., 2005; Holman & Murray, 2005). The symmetry of transits (even for large  $e$ ) means that transit times are less susceptible to degeneracies than other system parameters, such as transit duration, impact parameter and limb darkening (Colón & Ford, 2009).

Transit timing deviations arising from planet–planet interactions depend sensitively on the masses and orbital configurations of the interacting planets. TTV analysis therefore provides a powerful method of determining masses (and therefore, in combination with their transit-derived radii, their densities). If TTVs are detected, follow-up investigations of *transit duration variations* can also be undertaken.

Planet–planet interactions are typically harder to detect via radial velocity measures, although this has been possible in a few cases, e.g. GJ 876 (Laughlin & Chambers, 2001; Rivera & Lissauer, 2001), HD 82943 (Tan et al., 2013), and 55 Cnc (Nelson et al., 2014b). Agol et al. (2005, Table 1) tabulated the expected TTV signals if these systems were to be observed as edge-on transiting systems.

**Forward and inverse problems** If the dynamical state of a transiting system could be fully specified, the associated transit times, transit durations, and their variations, could be derived from numerical integration of the equations of motion for gravitationally-interacting point masses (including, if appropriate, higher-order effects such as general relativistic and tidal terms).

The inverse problem, that of characterising the system architecture and dynamics responsible for any given observational set of transit times and transit durations, is substantially more challenging.

**Astrophysical interest** TTVs have been applied to various areas of exoplanet studies, for example, to confirm candidate planets in multi-transiting systems (through correlated or anti-correlated variations in two

or more candidates in the same system), to provide planet masses (and other orbit constraints) through their observed gravitational effects on other planets, to detect and characterise non-transiting planets in the same system (and thereby probe the distributions of coplanarity), to place limits on the presence of companions of hot Jupiters, and to detect more specific accompanying objects such as satellites (exomoons) or Trojans.

**Trojans and exomoons** The contribution of transit timing variations to the broader topics of the detection of Trojans and exomoons is considered separately in Sections 6.21 and 6.22 respectively.

**Other causes** Other effects which can also result in variations in transit times or durations are considered elsewhere, including star spots (§6.14.2), and orbit precession due to tidal interactions, host star oblateness, and general relativity (§6.19.4).

Non-dynamical effects due to binning or (stroboscopic) sampling can also mimic transit time variations (e.g. Kipping, 2010a; Mazeh et al., 2013; Szabó et al., 2013; Price & Rogers, 2014).

### 6.20.2 Classification of configurations

The types of transit timing variations that might be observed can be classified according to some broad consideration of possible system architectures.

Even before the first detections, the possibility of observing transit time variations had been studied in some detail (e.g. Miralda-Escudé, 2002; Borkovits et al., 2003; Agol et al., 2005; Holman & Murray, 2005; Heyl & Gladman, 2007; Nesvorný & Morbidelli, 2008; Nesvorný, 2009; Payne et al., 2010; Borkovits et al., 2011).

Amongst early findings was the fact that deviations from regular transit times should be particularly sensitive to bodies in resonant orbits, where timing accuracies of  $\sim 10$  s would allow the detection of Earth-mass planets in mean motion resonance (e.g. Agol et al., 2005; Holman & Murray, 2005; Heyl & Gladman, 2007).

Agol et al. (2005) gave an overview of four somewhat distinct system architectures likely to generate significant transit timing variations (see also, e.g., Nesvorný & Vokrouhlický, 2014). They derived estimates of the size of the associated transit timing variations,  $\delta t$ , arising from the following limiting cases: (i) an inner orbiting planet with a much smaller period; (ii) an outer perturbing planet on an eccentric orbit with a much larger period; (iii) both transiting and perturbing planets on circular orbits with an arbitrary but non-resonant period ratio; and (iv) planets on initially circular orbits locked in mean motion resonance.

Their formulation assumes that the orbits of both planets are aligned in the same plane, that the system is edge-on ( $i \sim 90^\circ$ ), and that the planet and star are

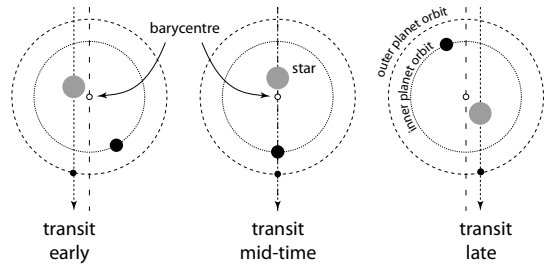


Figure 6.77: Schematic illustrating the change in transit times in a 3-body system. The transiting planet is the outer body in a 2-planet system; transit times are affected by the changing position of the host star with respect to the barycentre due to the other planet (a similar effect arises when the transiting planet is the inner body). The effect is present even if the gravitational interaction between the two planets is negligible. Since the star is itself moving with respect to the barycentre, transit durations are also affected. After Agol et al. (2005, Figure 1)

spherical such that the transit is symmetric with a well-defined midpoint. In the following summary of their analysis, subscripts 1 and 2 denote the inner and outer planets, and  $\mu$  denotes the planet-to-star mass ratio.

**(a) Negligible planet–planet perturbations** The assumption of negligible planet–planet perturbations, in a system shown schematically in Figure 6.77, requires that the pericentre of the outer planet is much larger than the apocentre of the inner,  $(1 - e_2)a_2 \gg (1 + e_1)a_1$ .

In this case, the inner binary orbits its barycentre, which in turn orbits the barycentre of the outer binary, and there is no additional perturbation due to planet–planet interactions: TTVs for the outer planet are due only to the star’s reflex motion due to the inner planet.

For circular orbits, the timing deviation of the  $m$ -th transit of the outer planet is (Agol et al., 2005, eqn 9)

$$\begin{aligned} \delta t_2 &\approx -\frac{P_2 a_1 \mu_1 \sin[2\pi(mP_2 - t_0)/P_1]}{2\pi a_2} \\ &\sim \mu_1 \left(\frac{a_1}{a_2}\right) P_2. \end{aligned} \quad (6.131)$$

If the outer planet is on an eccentric orbit, then to first order in  $a_1/a_2$  (Agol et al., 2005, eqn 14)

$$\delta t_2 = -\frac{P_2 \mu_1 r_1 \sin[\nu_1 + \tilde{\omega} i_1] \sqrt{1 - e_2^2}}{2\pi a_2 (1 + e_2 \cos \tilde{\omega}_2)}, \quad (6.132)$$

where  $\nu$  is the true anomaly (§2.1.1). Further details of this configuration are given by Borkovits et al. (2011). One example of such a configuration may be the candidate non-transiting hot Jupiter interior to the candidate KOI-1822 described by Millholland et al. (2016).

**(b) Exterior perturbing planet** The second case considered by Agol et al. (2005) includes *gravitational planet–planet interactions*. They assessed the timing

variations which result from the presence of a perturbing outer planet on an eccentric orbit whose semi-major axis is much larger than that of the inner transiting planet on a nearly circular orbit. In this limit, resonances are unimportant, and the small factor  $a_1/a_2$  can be used as argument for a perturbation expansion.

The outer planet changes the period of the inner planet by  $\mu_2(a_1/r_2)^3 P_1$ . As the distance of the outer planet changes due to its eccentricity, the inner planet's period also changes. Deviations in its transit timing accumulate over the period of the outer planet,  $P_2$ , with (Agol et al., 2005, eqn 25)

$$\frac{\delta t}{P_2} \sim \mu_2 e_2 \left(\frac{a_2}{a_1}\right)^3. \quad (6.133)$$

The inverted case of an inner perturbing and outer transiting planet lead to analogous transit timing variations, but observationally less compelling in that the transit time changes occur over much longer intervals, while the geometric transit probability is also much lower.

**(c) Circular non-resonant planets** More complex time-dependent behaviour occurs for gravitationally interacting but non-resonant planet pairs. Away from resonance, the perturbation to the orbit of each planet is small, and the interaction can be calculated using linear perturbation theory.

The planets interact most strongly at conjunction, where the perturbing planet causes a radial impulse to the transiting planet, increasing its eccentricity. Since the planets are not exactly in resonance, the longitude of conjunction drifts with time, causing the perturbations to cancel after the longitude has drifted by  $\approx \pi$  in the inertial frame. Accordingly, the eccentricity grows during half of the period of circulation of the longitude of conjunction.

The closer the planets are to a resonance, the longer the period of circulation, and thus the larger the eccentricity grows, with the change in eccentricity causing a change both in semi-major axis and mean motion (Agol et al., 2005, Figure 3). Half way between resonances the perturbations are small, of order

$$\mu_2 \left(\frac{a_1}{a_1 - a_2}\right)^2 P_1 \quad (6.134)$$

for the inner planet (and equivalently for the outer planet). Perturbations increase closer to a resonance.

**(d) Planets in resonance** Agol et al. (2005, Section 6) provide the following order-of-magnitude derivation of the transit timing variations for two planets in first-order mean motion resonance (cf. box, page 505).

Consider a first order,  $j:j+1$ , resonance where the lighter planet is a test particle. In resonance, the two planets have successive conjunctions at the same longitude in inertial space. The strong interactions that occur there build up the eccentricity of the test particle,

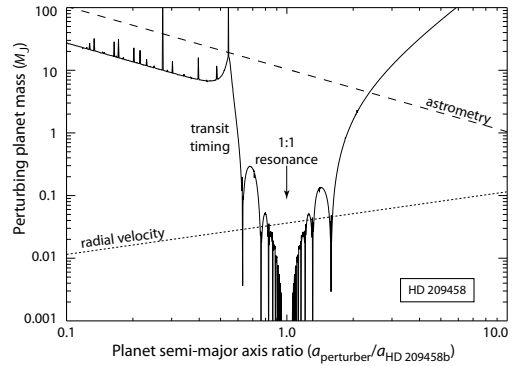


Figure 6.78: Comparison of techniques for detecting additional perturbing planets, as a function of perturber mass and orbit ratio. Computations are for HD 209458 ( $0.7M_J$ ), and circular orbits.  $10\sigma$  detection limits are shown for transit timing (solid line; 100 s timing sensitivity), astrometry (dashed;  $1\sigma$  accuracy of  $1\mu\text{as}$ ), and radial velocity (dotted;  $1\sigma$  accuracy of  $0.5\text{ m s}^{-1}$ ). Transit timing is more sensitive than astrometry for  $a_1/a_2 < 2$ . Away from resonance, radial velocity is more sensitive, while close to resonance transit timing is more sensitive. Astrometry and transit timing have the same slope at small semi-major axis ratios, since both probe the host star's reflex motion due to the inner planet. The solid curve is an upper limit to the minimum detectable mass, since  $e > 0$  gives larger timing variations. From Agol et al. (2005, Figure 7), © Oxford University Press.

and cause a change its semi-major axis and period. The change in period causes its longitude of conjunction to drift until, by about  $\pi$  relative to the original direction, the eccentricity begins to decrease, completing a libration cycle. The libration of the semi-major axes causes the timing of the transits to change.

This qualitative picture provides an estimate of the transit time variation. Within each libration cycle the longitude of conjunction shifts by about half an orbit, mostly due to the period change of the lighter planet. Since conjunctions occur only once every  $j$  orbits, the largest transit time deviation of the lighter planet during the period of libration is  $P/j$ .

Their more detailed analysis leads to their estimate of the transit timing variation for resonant systems (Agol et al., 2005, eqn 33)

$$\delta t_{\text{max}} \sim \frac{P}{4.5j} \left(\frac{m_{\text{pert}}}{m_{\text{pert}} + m_{\text{trans}}}\right). \quad (6.135)$$

If the perturber is more massive than the transiting planet, the timing variations are of the order of the period, independent of the perturber mass. For lighter perturbers, the timing variations are smaller than the period by the ratio of the perturber to transiting planet masses.

The resulting libration period is given by (Agol et al., 2005, eqn 34)

$$P_{\text{lib}} \sim 0.5j^{-4/3} \mu^{-2/3} P. \quad (6.136)$$

For example, an Earth-mass planet in 2:1 resonance with a  $P = 3\text{ d}$  transiting planet (such as HD 209458 b) would

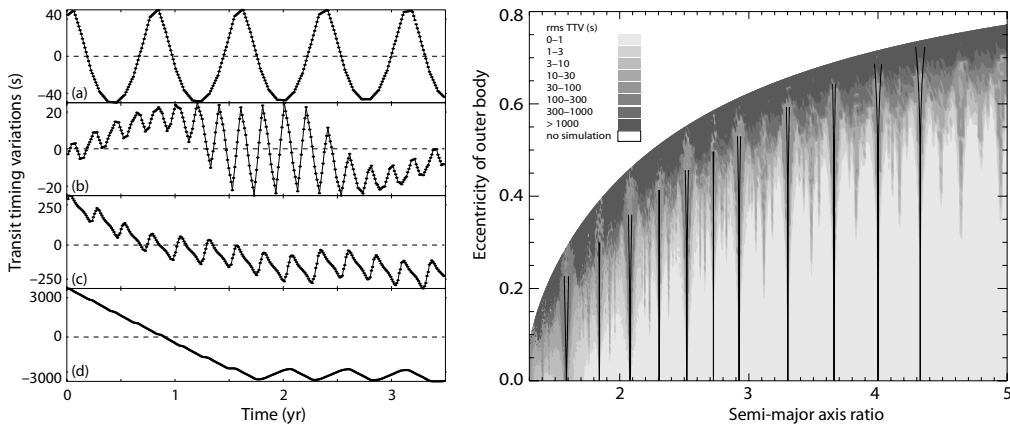


Figure 6.79: Left: transit timing variations for four systems over the nominal Kepler lifetime (3.5 yr). Each dot represents a transit. The curves correspond to (a)  $a_o/a_i = 3.6593$ ,  $e_o = 0.596$ ,  $\tilde{\omega}_o = 180^\circ$ , (b)  $a_o/a_i = 2.3313$ ,  $e_o = 0.395$ ,  $\tilde{\omega}_o = 0^\circ$ , (c)  $a_o/a_i = 1.5812$ ,  $e_o = 0.204$ ,  $\tilde{\omega}_o = 0^\circ$ , (d)  $a_o/a_i = 1.5812$ ,  $e_o = 0.219$ ,  $\tilde{\omega}_o = 0^\circ$ . A wide variety of patterns is exhibited by the TTV curves. Right: median rms TTV amplitude for 5 different initial orbit configurations and 10 yr of (874) consecutive transits for a  $1M_J$  hot Jupiter on a circular orbit at 0.05 au, and a  $1M_\oplus$  external perturber with orbit parameters indicated. Contour levels in this ‘flames of resonance’ diagram are shown in s. Resonant libration widths for selected period commensurabilities are shown as black lines. From Veras et al. (2011a, Figures 1 and 2), by permission of IOP Publishing/AAS.

cause variations of  $\sim 3$  min over a year. Their comparison of such a transit timing probe, with astrometric and radial velocity techniques, is shown in Figure 6.78.

Nesvorný & Vokrouhlický (2016a) provide an analytical model, valid for small  $e$ , to aid the interpretation of resonant transit timing variations. Thus the period of resonant transit timing variations is  $\propto (m_{\text{pert}}/M_\star)^{-2/3}$ , such that for  $m_{\text{pert}}/M_\star = 10^{-4}$ , for example, the TTV period exceeds the orbital period by about  $\times 100$ .

### 6.20.3 Other treatments of perturbed systems

Expanding on the above treatment by Agol et al. (2005), various studies have examined the pronounced TTVs expected in particular resonant and near-resonant systems, i.e. when the ratio of orbital periods are (nearly) equal to a ratio of small integers. The description of planetary properties from (near-)resonant TTVs, however, is complicated by various degeneracies due to limitations in information content, resolvable only under certain assumptions (e.g. Veras et al., 2011a; Boué et al., 2012c; Lithwick et al., 2012; Nesvorný & Vokrouhlický, 2014). Example results are shown in Figure 6.79.

In the following, some specific studies are used to illustrate some of the patterns of TTVs which may be expected to arise in various situations.

**Inclined and retrograde systems** Payne et al. (2010) considered a 2-planet system comprising a transiting hot Jupiter ( $M_1 = M_J$ ,  $e_1 = 0$  and  $a_1 = 0.05$  au) and a small non-transiting  $1M_\oplus$  planet which perturbs its transit times. The systems are followed numerically for  $\sim 10$  yr ( $\sim 1000$  transits of the more massive planet) for various inclined and retrograde configurations.

Figure 6.80a shows a hot Jupiter on a circular orbit at 0.05 au, perturbed by a ( $1M_\oplus$ ,  $e_2 = 0.02$ ) companion located on the external 2:1 mean motion resonance. Although the prograde systems ( $0^\circ \leq i \leq 90^\circ$ ) have TTV profiles that differ significantly, their overall amplitudes are similar. In contrast, the amplitude of the  $i = 180^\circ$  signal is very low ( $\sim 1$  s). Results for the 3:1 case (Figure 6.80b) are qualitatively similar.

For the 5:1 resonance system (Figure 6.80c), in contrast, the amplitude of the  $i = 180^\circ$  signal remains extremely low, but now with significant differences in the behaviour at smaller angles: the  $i = 0^\circ$  and  $i = 180^\circ$  now have similarly low amplitudes, with an approximate maximum occurring at  $i = 90^\circ$ .

Away from resonance (Figures 6.80d–f), the  $i = 180^\circ$  signal remains low, but otherwise with a more complex dependence on inclination. Some cases have the highest amplitude at  $i = 0^\circ$  (Figures 6.80d & 6.80f), while the low eccentricity plot of Figure 6.80e has a particularly low amplitude signal at  $i = 0^\circ$ .

There are a number of frequencies evident in Figure 6.80, with periods from a few months to  $\gg 10$  yr. In general, the short-term oscillations tend to be driven by variations in  $e_2$ , leading to variations in the distance of closest approach. The longer term quadratic trends are primarily due to outward drifts in  $a_2/a_1$  as a result of perturbations at close approach.

Their broad conclusions were that in the vicinity of exterior mean motion resonances the inclination dependence is complex: low order resonances maintain a high TTV amplitude for all regions  $i < 170^\circ$ , declining in amplitude only for low eccentricity cases close to

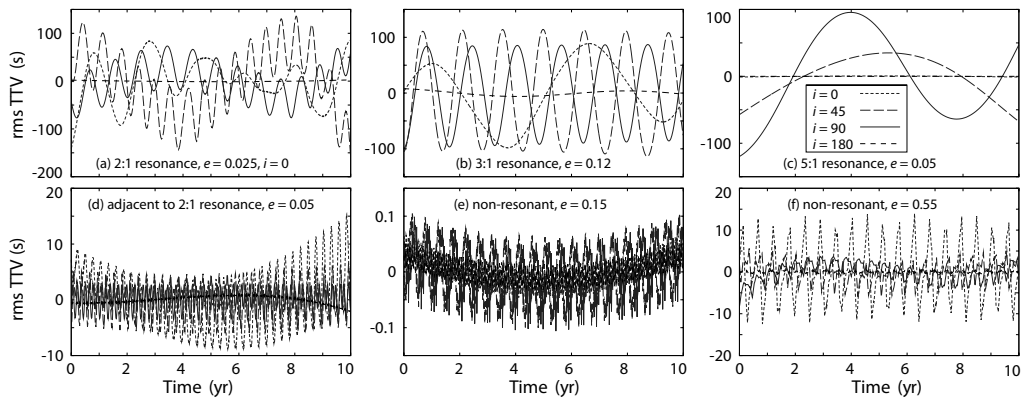


Figure 6.80: TTVs at fixed  $a$  and  $e$  (all with  $e_1 = 0$ ), for varying inclinations. Results for prograde orbits ( $i = 0^\circ, 45^\circ$ , and  $90^\circ$ ) and a retrograde orbit ( $i = 180^\circ$ ) are shown. Panels give results for: (a) on/near the 2:1 mean motion resonance ( $a_2/a_1 = 1.59$ ,  $P_2/P_1 = 2.0$ ,  $e_2 = 0.02$ ); (b) the 3:1 resonance ( $a_2/a_1 = 2.08$ ,  $P_2/P_1 = 3.0$ ,  $e_2 = 0.12$ ); (c) the 5:1 resonance ( $a_2/a_1 = 2.92$ ,  $P_2/P_1 = 5.0$ ,  $e_2 = 0.05$ ); (d) just outside the 2:1 resonance ( $a_2/a_1 = 1.63$ ,  $P_2/P_1 = 2.08$ ,  $e_2 = 0.05$ ); (e) a non-resonant system at low eccentricity ( $a_2/a_1 = 3.6$ ,  $P_2/P_1 = 6.83$ ,  $e_2 = 0.15$ ); (f) a non-resonant system at high eccentricity ( $a_2/a_1 = 3.6$ ,  $P_2/P_1 = 6.83$ ,  $e_2 = 0.55$ ). The results are very sensitive to the precise orbital configurations, with different systems exhibiting differing frequency contributions, with many contributions having different dependencies on inclination. In all examples, the TTV signal for  $i = 180^\circ$  tends to be of lower amplitude than for other inclinations. From Payne et al. (2010, Figure 1), by permission of IOP Publishing/AAS.

$i = 180^\circ$ , whereas higher order resonances display an increase in TTV amplitude as inclinations rise from 0 to  $45^\circ$ . Regions immediately adjacent to resonance show extreme sensitivity to changes in perturber  $a$ ,  $e$  and  $i$ .

Exterior perturbers away from resonances show a slow decrease in TTV amplitude with increasing inclination, although regions adjacent to resonances can show remarkably complex behaviour. Interior perturbers display a slightly different behaviour. Away from resonance the amplitude remains approximately constant with inclination, but around resonance the perturbations become *stronger* as the inclination increases towards  $90^\circ$  before decreasing again beyond  $90^\circ$ .

**Step-like changes and ‘chopping’** For tight orbital spacings, which is common amongst Kepler planets, the effect of a single conjunction can be described in terms of a step-like change of the transit time (with subsequent transits of the inner planet being delayed, and those of the outer planet being sped up), accompanied by a discrete change in sampling of the underlying oscillations from eccentricity-related interaction terms (Nesvorný & Vokrouhlický, 2014).

In the limit of small orbital eccentricities, Nesvorný & Vokrouhlický (2014) gave expressions for these effects as a function of mass and orbital separation. Examples for the cases of Kepler-36 c and Kepler-247 are shown in Figure 6.81.

In practice, the long-term effects of conjunctions, in which  $\delta t_i$  accumulates over many periods of the synodic angle, will be absorbed as a small change in the (nominal) orbital period. The short-period effects of conjunctions in contrast, described as *chopping* (e.g. Holman et al., 2010; Carter et al., 2012; Deck & Agol, 2015), are particularly distinctive, with the resulting TTV signal having a saw-tooth profile, each tooth marked by a few rising and declining transits. These characteristic features provide the possibility of determining the companion mass (Nesvorný & Vokrouhlický, 2014; Deck & Agol, 2015).

#### 6.20.4 Orbits and masses

**Modeling** The task of inverting a set of transit times (and possibly durations) to recover the masses and orbits of the constituent planets over an adequate sampling of parameter space, is challenging. This is in part due to its computational expense, but also because numerous different perturber mass-orbit configurations can lead to degenerate solutions (e.g. Nesvorný & Morbidelli, 2008; Nesvorný, 2009; Veras et al., 2011a).

This *inverse problem* involves fitting a model of gravitationally-interacting planets to the data. However, each model evaluation requires numerical integration of an N-body system for often hundreds of orbits and determining the transit times. Even when a best-fit solution has been found, Markov chains used to determine parameter uncertainties can require of order  $10^7$  model evaluations to converge (Deck et al., 2014b).

The problem is compounded if a wider parameter space must be searched, such as when one of the interacting planets is not transiting.

Possible biases in the masses determined in this way, relevant in considerations of internal structure and the mass-radius relation, are discussed by Steffen (2016).

In general, there is no simple analytic solution for a given TTV signal. In the case of planetary pairs near first-order mean motion resonance, an approximation has been formulated, although there remains an unresolved degeneracy between masses and free eccentricities. This special case is discussed explicitly below.

Full numerical integrations, or a more accurate formula, could break this degeneracy. Transit times would have to be measured precisely enough such that higher-

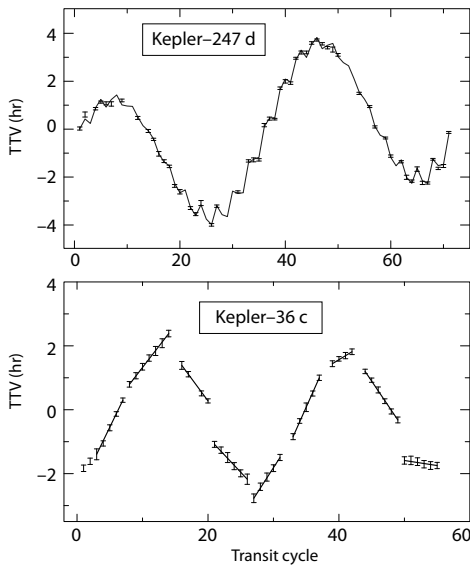


Figure 6.81: Effect of conjunctions on the TTVs of Kepler–247 d and Kepler–36 c. The solid line for Kepler–247 d shows the best dynamical fit from Nesvorný et al. (2014a) corresponding to a (non-transiting)  $2.4M_J$  companion and an outer orbit just within the 3:1 resonance. TTVs of Kepler–36 c are caused by the transiting super-Earth Kepler–36 b, with an orbit in 7:6 resonance with Kepler–36 c. Line segments highlight the discontinuous nature of the TTVs. From Nesvorný & Vokrouhlický (2014, Figure 1), by permission of IOP Publishing/AAS.

order effects can be included (Deck et al., 2014b).

Example systems for which TTVs (combined with TDVs) can yield measurements of the full orbital state of a system from photometry alone, are Kepler–36 (Carter et al., 2012), Kepler–46 (Nesvorný et al., 2012) and Kepler–88 (Nesvorný et al., 2013a).

**Algorithmic implementation** Various algorithms have been provided for the problem of transit timing inversion, typically with corresponding radial velocities. These include:

**Swarm-NG**: a parallelised GPU-based code (Dindar et al., 2013).

**TRADES**: the ‘TRANSits and Dynamics of Exoplanetary Systems’ was developed to simultaneously fit radial velocities and transit times (Borsato et al., 2014; Borsato, 2016; Nespral et al., 2017). It includes a dynamical simulator for N-body systems, which also fits the data during orbit integration and determines the optimum set of orbit parameters using grid search,  $\chi^2$  minimisation, genetic algorithms, particle swarm optimisation, and bootstrap analysis.

**TTVFast**: a numerical integration code for the computation of transit times, using a symplectic integrator with Keplerian interpolator (Deck et al., 2014a,b). Given the system’s dynamical state at some reference time, along with the (relative) planetary masses, the code integrates the Newtonian equations of motion for gravitationally-interacting point masses (ignoring general relativistic and tidal effects). Throughout the integration, the code checks for planet transits (defined via projected distances and their geometrical sign), from which it determines the transit time as well as the orbital state (sky-projected astrometric position and velocity) at that time. These quantities can

then be used to determine the transit duration, or as input to a photometry (or photo-dynamical) model. The code can also determine the stellar radial velocity at a set of supplied times when both radial velocity and TTV data are available.

**TTVfaster**: implementation of an analytic TTV approximation, to first-order in  $e$  and  $M_p/M_\star$  (Agol & Deck, 2016a,b).

**Photo-dynamical approach** Nesvorný et al. (2014a) describe their 2-step *photo-dynamical* approach to fitting TTVs. In the first step, they fit a transit model to the Kepler photometry, giving time, duration, and other basic parameters of each transit, and their relative uncertainties. In the second step, they model the inferred transit times and durations as being caused by the gravitational interaction with a stellar, planetary, or exomoon companion. As such, it is part of a broader effort to search for exomoons through transit timing (§6.22.2).

Dynamical fits are obtained from the mid-transit times for a 10-parameter model, comprising the mass ratios  $M_1/M_\star$  and  $M_2/M_\star$ , orbital period ratio  $P_2/P_1$ , eccentricities  $e_1$  and  $e_2$ , pericentre longitudes  $\tilde{\omega}_1$  and  $\tilde{\omega}_2$ , mean longitude  $\lambda_2$ , nodal longitude difference  $\Delta\Omega = \Omega_2 - \Omega_1$ , and inclination  $i_2$  (with indices 1 and 2 denoting transiter and perturber, respectively).

They applied this approach to the candidate systems KOI–227, KOI–319, and KOI–884 (Kepler–247). In the latter two cases, the TTVs of the inner transiting planet led to the detection of an outer non-transiting planet, close to a 3:1 or a 5:3/7:3 resonance respectively.

**Analytic perturbation theory** As an alternative to direct N-body integrations, Nesvorný & Morbidelli (2008) described modeling using perturbation theory. They found that unique characterisation of the perturbing planet requires high precision on the measured transit times, typically at the level of 15–30% of the full variation amplitude. Timing of secondary transits, if measured with adequate precision, could help to resolve the degeneracies. The method was extended to eccentric transiting planets and inclined orbits by Nesvorný (2009).

**Systems near first-order resonance** The Kepler results have highlighted the fact that most planet pairs in the Kepler data that have measured transit time variations are near first-order mean motion resonances. Anti-correlated sinusoidal transit timing variations are then related to the ‘super-period’ of the two planets (§10.8.1).

Lithwick et al. (2012) derived analytical formulae for their TTV signals, by separating the planet’s eccentricity into ‘free’ and ‘forced’ parts, where the forced part is purely due to the planets’ proximity to resonance. They showed that the phase of the TTV depends sensitively on the presence of free eccentricity: if the free eccentricity vanishes, the TTV will be in phase with the longitude of conjunctions, an effect detectable in current TTV data. The TTV amplitude depends on planet mass and free eccentricity, and it determines planet mass uniquely only when the free eccentricity is sufficiently small.

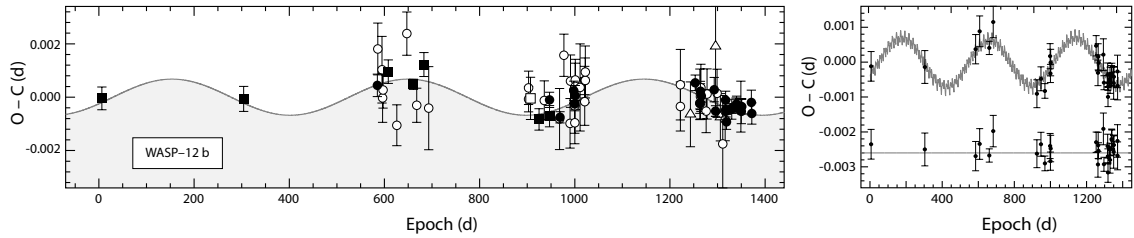


Figure 6.82: Left: transit time observations from the study of WASP-12 b by Maciejewski et al. (2013a). Circles denote their observations, squares denote literature values, and triangles denote timing by amateur observers. Filled symbols denote errors smaller than 40 s. The postulated sinusoidal variation is shown with the solid line. Right: predicted and observed transit time variations for a proposed 2-planet model from combined radial velocity and transit time observations (the residuals are offset below). From Maciejewski et al. (2013a, Figures 5 and 8), reproduced with permission © ESO.

Lithwick et al. (2012) gave analytical expressions for transit time variations for two co-planar planets lying near (but not in) a first-order  $j : j - 1$  mean motion resonance, with normalised distance to resonance

$$\Delta \equiv \frac{P'}{P} \frac{j-1}{j} - 1, \quad (6.137)$$

where  $P$  and  $P'$  are the periods of the inner and outer planets. The amplitude and phase of the transit time variations (their Equations 8–9) depend on both planet mass and free eccentricity according to

$$V = P \frac{\mu'}{\pi j^{2/3} (j-1)^{1/3} \Delta} \left( -f - \frac{3}{2} \frac{Z_{\text{free}}^*}{\Delta} \right), \quad (6.138)$$

$$V' = P' \frac{\mu}{\pi j \Delta} \left( -g + \frac{3}{2} \frac{Z_{\text{free}}^*}{\Delta} \right), \quad (6.139)$$

where  $\mu$  is the mass ratio of the inner planet to the star and  $\mu'$  that of the outer planet, and  $f$  and  $g$  are sums of Laplace coefficients (with values of order unity, and with  $f < 0$  and  $g > 0$ ), and \* denotes complex conjugate.

When the pair is far from resonance,  $|\Delta|$  is of order unity, and the expression reduces to  $\sim P\mu$ . The dynamical quantity that controls the transit time variation is

$$Z_{\text{free}} \equiv f z_{\text{free}} + g z_{\text{free}}', \quad (6.140)$$

which is a linear combination of the free complex eccentricities of the two planets. They define the complex eccentricity of a planet as

$$z = e e^{i\tilde{\omega}}, \quad (6.141)$$

where  $\tilde{\omega}$  is the longitude of pericentre. Near a first-order mean motion resonance, this can be decomposed into free and forced parts,

$$z = z_{\text{free}} + z_{\text{forced}}. \quad (6.142)$$

The planet's ‘forced eccentricity’ is forced by virtue of its companion's proximity to resonance. The ‘free eccentricities’ represent the degrees of freedom associated

with the non-circularity of the orbits, and can take arbitrary values. Although there are four such degrees of freedom ( $e, \tilde{\omega}, e', \tilde{\omega}'$ ), they only affect the TTV signal through the linear combination of Equation 6.140.

The observed TTV signals can then be inverted to obtain physical parameters. There is an inherent degeneracy between mass and free eccentricity which in general prevents either from being determined independently of the other. The degeneracy can be approached statistically, yielding a measure of the typical eccentricity and mass–radius relationship for pairs of planets near first-order resonances with low free eccentricities (Hadden & Lithwick, 2014).

In their analysis of the TTV signals of six short-period Kepler pairs, Lithwick et al. (2012) found that three (Kepler-18, Kepler-24, Kepler-25) have a TTV phase consistent with zero, while the others (Kepler-23, Kepler-28, Kepler-32) have small but non-zero TTV phases, from which they derive approximate masses.

The smallness of the free eccentricities suggests that the planets have experienced substantial dissipation, consistent with the idea that the observed pile-up of Kepler pairs near mean motion resonances is caused by resonant repulsion (§6.30.4). The fact that some have non-vanishing free eccentricity suggests that after resonant repulsion there was a subsequent phase in the planets' evolution when their eccentricities were modestly excited, perhaps by planet–planet interactions.

**Systems near second-order resonance** Studies of Kepler multiple planet candidates show that first-order resonances dominate, but that second-order resonances are also present (§6.30.4). Details of the transit timing variations of two planets on nearly circular orbits near a second-order mean motion resonance are given by Deck & Agol (2016): they are approximated anti-correlated, with phases  $\phi$  and  $\sim \phi + \pi$ , where  $\phi$  also depends on the eccentricities and longitudes of pericentre, such that the resulting transit timing variations do not in general uniquely determine both planet masses, eccentricities, and pericentres.



### 6.20.5 Observations from the ground

TTV studies were made for many systems, including CoRoT-1 (Bean, 2009); GJ 436 (Alonso et al., 2008b; Bean et al., 2008a; Coughlin et al., 2008; Cáceres et al., 2009); HAT-P-3 (Gibson et al., 2010b); HD 189733 (Miller-Ricci et al., 2008a; Hrudková et al., 2010); HD 209458 (Brown et al., 2001; Agol & Steffen, 2007; Miller-Ricci et al., 2008b); OGLE-TR-111 b (Díaz et al., 2008; Adams et al., 2010a); OGLE-TR-113 b (Adams et al., 2010b); TrES-1 (Steffen & Agol, 2005; Rabus et al., 2009b,c); TrES-2 (Mislis & Schmitt, 2009; Rabus et al., 2009c); TrES-3 (Gibson et al., 2009); WASP-3 (Gibson et al., 2008; Maciejewski et al., 2010); and XO-1 (Cáceres et al., 2009). For OGLE-TR-111 b, variations reported by Díaz et al. (2008) were not confirmed by Adams et al. (2010a).

Efforts to detect TTVs of hot Jupiters from ground-based observations have resulted in no unambiguous results (Maciejewski et al., 2013a).

**TTV detections from the ground** For WASP-3 b, TTVs of 1–2 min were reported by Maciejewski et al. (2010). Their favoured explanation was a second planet of  $15M_{\oplus}$  located close to the outer 2:1 resonance.

For WASP-12, Maciejewski et al. (2013a) obtained 61 transit light curves between 2009–12 from 13 observatories (Figure 6.82). Transit timings and radial velocity measurements each gave marginal support for the presence of a second planet, while a combined analysis resulted in an improved two-planet model. They suggest that there is an additional  $0.1M_J$  body on a  $P = 3.6$ -d eccentric orbit which, from a dynamical analysis, would be located in a relatively wide stable zone.

For HAT-P-13 b, Pál et al. (2011) observed a 0.01 d departure from a linear ephemeris. This was confirmed by Nascimbeni et al. (2011b) who modeled a sinusoidal variation with  $P = 1150$  d and semi-amplitude 0.005 d. Such a signal could not be caused by planet c, suggesting existence of a third planet. Specific ‘jumps’ in the transit time ephemeris, noted by Pál et al. (2011), suggested a long-period eccentric perturber near pericentre.

Although neither confirmed or excluded by later observations (Nascimbeni et al., 2011b), such behaviour is found in the simulations of Holman & Murray (2005). In contrast, Fulton et al. (2011) showed that all mid-transit times except that from earlier work by Szabó et al. (2010) are consistent with a linear ephemeris. A similar conclusion was reached by Southworth et al. (2012a).

### 6.20.6 Contributions from Kepler

**Introduction** Astrophysically interesting deviations from a linear transit ephemeris that are potentially observable by Kepler can be caused most readily by a perturbing planet or exomoon, although perturbations by a stellar companion or higher-order gravitational effects can occasionally be significant (Ford et al., 2011).

Demonstration of (correlated) TTVs in a given system provides evidence that the candidates are true planets, and leads to mass estimates for many of them.

Investigations of Kepler transit timing variations proceeds by first determining the set of transit times for each transiting object under study. With reference to the best-fit linear ephemeris, the set of transit times can then be assessed for excess scatter, for long-term trends, and for simple periodic variations. Various detailed statistical tests have been developed and applied, not necessarily with the goal of definitively ruling on their significance, but more with the intention of identifying candidates for further detailed study (e.g. Ford et al., 2011, 2012b; Steffen et al., 2012b; Xie, 2013; Mazeh et al., 2013; Holczer et al., 2016; Ofir et al., 2018). Modeling of the observed transit time variations, from which the system’s physical characteristics are derived, thereafter proceeds on a case-by-case basis.

For multi-planet transiting systems, the first indications of significant *anti-correlations* in the TTVs, even though some of the individual signals did not reach the significance thresholds, were reported by Ford et al. (2011, 2012a) and Steffen et al. (2012a). If the relationship between TTVs of multi-candidate systems can be proven to be non-random, it significantly weakens the probability that the candidate signals are due to false-positives (Ragozzine & Holman, 2010), even if the properties of the planets cannot be inferred directly.<sup>5</sup>

**First Kepler systems confirmed by TTV** Significant transit time variations were first detected for the 2-planet transiting system Kepler-9 from seven months of Kepler observations (Holman et al., 2010). Their 19.2- and 38.9-d orbital periods are increasing and decreasing at about 4 and 39 min per orbit respectively, explicable by gravitational interaction of two bodies near a 2:1 orbital resonance, and therefore an example of a system in which the gravitational interaction and resulting TTVs are dominated by proximity to mean motion resonance (Figure 6.83). The transit times of the inner body display an additional variation of smaller amplitude.

The transiting 6-planet system Kepler-11 (Lissauer et al., 2011a) includes five planets with periods in the range 10–47 d, and a sixth with a longer period (Figure 6.19). Rather than driven by proximity to resonance, the TTVs for each planet are dominated by the perturbations from its immediate neighbours. The relative periods and phases of each pair of planets, and to a lesser extent the small eccentricities, determine the shapes of

<sup>5</sup>Early Kepler header data gave an erroneous system time (TDB rather than UTC; box, page 104), such that absolute barycentric times were in error by  $\sim 1$  min ([archive.stsci.edu/kepler/timing\\_error.html](http://archive.stsci.edu/kepler/timing_error.html), 2012 November). Whilst internally consistent, differences could be apparent when comparing Kepler times to other timing observations.

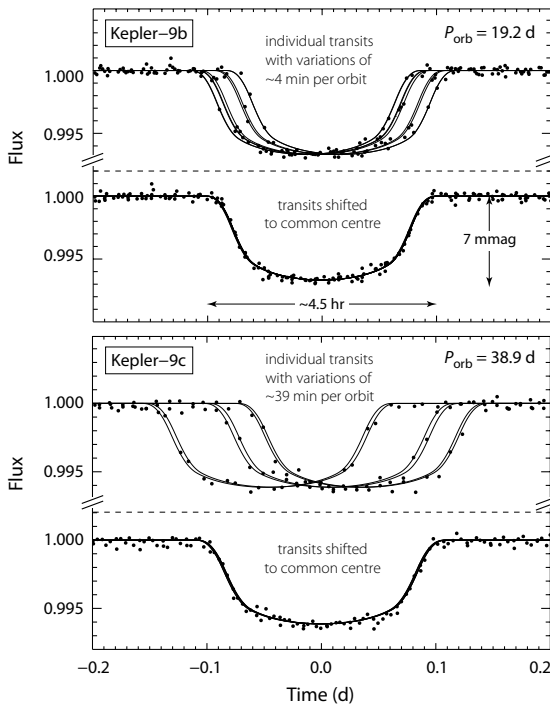


Figure 6.83: Transit curves for *Kepler-9b* and *Kepler-9c*. In both panels, the top curve shows the data folded with the best-fit period. Displacements between different transits are due to transit time variations from gravitational interactions between the planets (in the original colour figure, data points from different transits are distinguishable). The bottom curves show the transits shifted to a common centre. From Holman et al. (2010, Figure 5), reprinted with permission from AAAS.

the curves, while the mass of each perturber determines the amplitudes. Thus this early TTV analysis provided masses for the inner five planets, along with constraints on their eccentricities (Lissauer et al., 2011a, Table 1).

Since these first examples, the majority of Kepler planet mass estimates have been derived from TTVs. TTVs currently provide the only method of measuring masses of terrestrial planets in the habitable zone of a Sun-like star (Steffen et al., 2012b).

**Other Kepler examples** Other representative systems with large TTVs include: *Kepler-18* (Cochran et al., 2011); *Kepler-23* and *Kepler-24* (Ford et al., 2012a); *Kepler-25*, *Kepler-26*, *Kepler-27*, and *Kepler-28* (Steffen et al., 2012a); *Kepler-29*, *Kepler-30*, *Kepler-31*, and *Kepler-32* (Fabrycky et al., 2012); and *Kepler-85*, *Kepler-279*, *Kepler-305* and *Kepler-396* (Ming et al., 2013).

An example of the observed TTVs is shown for the *Kepler-30* system in Figure 6.84.

Data from *Kepler-K2* show that *WASP-47*, a previously known hot Jupiter host, also hosts two additional transiting planets: a Neptune-sized outer planet (planet d) in a 9-d orbit, and a super-Earth inner com-

panion in a 0.8-d orbit (Becker et al., 2015). TTVs detected in the *K2* light curve confirm the planetary nature of the outer planet, and provide masses of two of the planets (b and d), and limits on the third (planet e).

**Systems with very large TTVs** A few Kepler systems show particularly pronounced TTVs:

*Kepler-30*: comprises a super-Earth, a Jupiter, and a Saturn, nearly in a 1:2:5 resonance. *Kepler-30c* has transit time variations of 1.7 h (Tingley et al., 2011c).

*Kepler-88*: with two planets just wide of the 2:1 resonance. *Kepler-88b*, their ‘king of transit variations’, has TTVs of 12 h (Nesvorný et al., 2013a; Barros et al., 2014b).

*Kepler-90g*: has the largest TTVs to date, with 25.7 h variations in consecutive transits (Cabrera et al., 2014).

**Development of the field** Kepler TTV candidates, and associated statistical tests and other insights, are reported in a series of papers (e.g. Ford et al., 2011, 2012a; Steffen et al., 2012a; Fabrycky et al., 2012; Ford et al., 2012b; Steffen et al., 2012b, 2013; Mazeh et al., 2013; Montet & Johnson, 2013; Xie, 2013; Xie et al., 2014; Xie, 2014b). The following gives a short chronology, illustrating the principal lines of development.

Ford et al. (2011), on the basis of 1235 transiting candidates from the first four months of data, found that at least 11% of those suitable for TTV analysis show evidence of TTVs, representing at least 65 TTV candidates.

Ford et al. (2012a) quantified their statistical significance based on the correlation of two TTV data sets. It was applied to an analysis of two stars with multiple transiting planet candidates (*Kepler-23* and *Kepler-24*), confirming four transiting planets in two systems.

Steffen et al. (2012a) used a Fourier analysis of transit times to demonstrate *anti-correlations* in the transit times in the same system, thereby identifying four new systems, *Kepler-25*, *Kepler-26*, *Kepler-27* and *Kepler-28*, containing a total of eight planets. Fabrycky et al. (2012) identified four further multiple interacting systems, *Kepler-29*, *Kepler-30*, *Kepler-31*, and *Kepler-32*.

Ford et al. (2012b) reported an updated TTV analysis for 1481 planet candidates based on the first 16 months of observations. They identified 39 strong TTV candidates based on long-term trends, and a further 136 weaker TTV candidates based on the excess scatter of TTV measurements about a linear ephemeris. The occurrence rate of TTVs is significantly increased in multiple transiting candidate systems.

Steffen et al. (2012b) analysed TTVs through the first six quarters, conducting two statistical tests for all KOIs, and a related statistical test for all pairs of KOIs in multi-transiting systems, identifying several systems which show potentially significant TTVs.

Steffen et al. (2013) confirmed 27 planets in 13 systems by showing the existence of statistically significant anti-correlated transit timing variations, and long-term

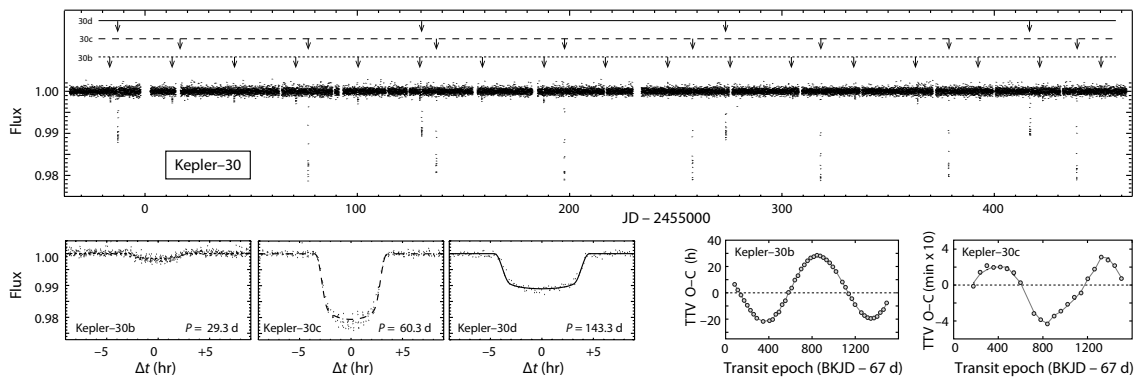


Figure 6.84: Top: normalised light curve for Kepler-30. Transit times of the three planets (b, c, d) are indicated by arrows, with the shallowest eclipses due to planet b (connected by the dotted line), the deepest to planet c (dashed), and the intermediate to planet d (solid). Lower left three: cumulative light curves for each planet, with each transit shifted to its measured mid-time, and with the transit models indicated. Lower right pair: the observed transit times, and theoretical model, for the interaction between planets Kepler-30 b and Kepler-30 c (star spot effects are evident in the latter). Top and lower left three from Fabrycky et al. (2012, Figures 6–7). The lower two show the improved model from Panichi et al. (2017a, Figure 1), by permission of IOP Publishing/AAS.

dynamical stability, which places limits on the candidate masses (showing that they are planetary). All confirmed systems have orbital periods near first-order mean motion resonances, with six systems near the 2:1 resonance, five near 3:2, and one each near 4:3, 5:4 and 6:5.

Mazeh et al. (2013) derived transit times for 1960 KOIs. Including systems found previously, they identified 130 KOIs that showed significant TTVs, and 13 that had short-period small-amplitude TTVs.

Montet & Johnson (2013), based on earlier work by Meschiari & Laughlin (2010), demonstrated the combination of TTVs with radial velocity measurements to determine planet masses, and applied it to Kepler-18.

Xie (2013) extracted TTVs for 12 pairs of transiting candidates near first-order mean motion resonances, using Q0–Q14 data. The Kepler-82 pair show high mass and density ratios, suggesting different internal compositions. Some subsequently-confirmed planets are also near mean motion resonances with other candidates, forming resonance chains, such as Kepler-80.

Xie et al. (2014) searched for sinusoidal TTVs in 2600 Kepler candidates, finding that TTV fractions rise significantly with transit multiplicity (Figure 6.85). Systems where four or more planets transit have a TTV fraction that is five times higher than those where a single planet transits, and about twice those for doubles and triples.

Xie (2014b) confirmed 30 more planets in 15 multi-planet systems, using data from Q0–Q16. All are near first-order resonances, and all show sinusoidal TTVs.

Ofir et al. (2018) developed a ‘spectral detection approach’ which assumes that a sinusoidal TTV exists, then calculates the improvement to  $\chi^2$  compared with a linear ephemeris. The technique expands detections to lower TTV amplitude, shorter period, and shallower transit depth, and resulted in 129 new periodic TTVs.

**Properties** In total, some 3–10% of Kepler systems show significant TTVs (Mazeh et al., 2013; Xie et al., 2014; Hadden & Lithwick, 2016; Jontof-Hutter et al., 2016; Hadden & Lithwick, 2017), although not all will necessarily be uniquely invertible (Deck et al., 2014b).

The full mission (17-quarters) transit timing catalogue (Holczer et al., 2016) includes 2599 KOIs, with times, durations and depths of 69 914 transits of 779 high S/N candidates. Including previous discoveries gives a total of 260 KOIs with long-term variations above 100 d.

A significant feature of the Kepler discoveries is that while the spacing between planets in a system appears to be roughly random, there is a distinct pile-up of planet pairs just wide of certain resonances, and a nearly empty gap just narrow of them (Lissauer et al., 2011b; Fabrycky et al., 2014), a phenomenon discussed further in Section 6.30.4. In turn, most Kepler planet pairs that have measured transit time variations are near first-order mean motion resonances.

The occurrence of TTVs as a function of multiplicity and planet spacing suggest that there are (at least) two different classes of Kepler systems, one closely packed, and one more sparsely populated (e.g. Xie et al., 2014).

**Comparison with masses from radial velocities** For planets with  $R_p \lesssim 8R_\oplus$ , masses measured via radial velocities are systematically larger than the those measured by TTVs, a finding which cautions any interpretation of the resulting mass–radius relation (Steffen, 2016; Mills & Mazeh, 2017). Mills & Mazeh (2017) found that the techniques agree for  $P < 11$  d, and suggest that the results are consistent with a radial velocity detection-sensitivity bias at longer periods.

**Spin dynamics** Delisle et al. (2017) show that planet–planet perturbations can drive a planet in an otherwise tidally locked spin–orbit resonance into non-synchronous (sub- or super-synchronous) spin–orbit resonances, or even chaotic states. Transit timing variations provide a probe, being dominated by

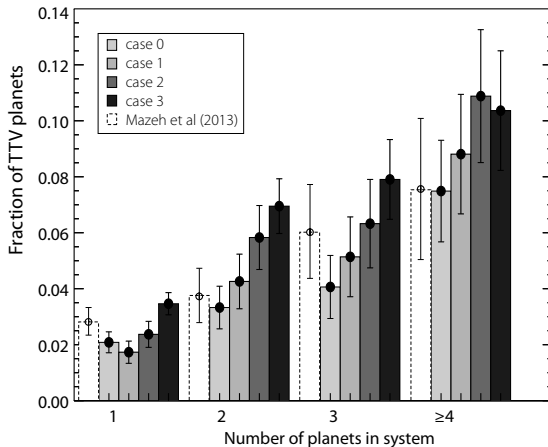


Figure 6.85: Measured TTV fraction in Kepler systems with (horizontal axis) 1, 2, 3, and 4 or more planets, for four combinations of selection thresholds (case 0 to case 3, progressively corresponding to more relaxed identification criteria). Within each transit group, the TTV fractions rise as the criterion for identifying TTV candidates is relaxed. The occurrence rate of sinusoidal TTV is much lower in 1-planet systems than those in higher multiples. Results obtained using the TTV catalogue of Mazeh et al. (2013), with selection criteria equivalent to case 0, are consistent with these values. From Xie et al. (2014, Figure 3), by permission of IOP Publishing/AAS.

perturbations of the planet's mean longitude. Their models show that Kepler-88 b may be in a chaotic rotation state.

### 6.20.7 Non-transiting planets

Various transiting candidates show significant TTVs but without any other detected transiting companion. The most natural explanation is that an accompanying perturbing planet exists, but orbits either in a non-coplanar configuration (e.g. §6.15.1), or with a comparable inclination but located at a larger separation for which the larger impact parameter fails to result in transits.

A more exotic explanation is that the planet is accompanied by a resonant Trojan companion (§6.21), as hypothesised for KOI-103.01 (Janson, 2013).

There are a number of cases where such TTVs have been used to infer the existence of additional *non-transiting planets* in the same system, amongst them Kepler-19 c (Ballard et al., 2011b), Kepler-46 c (Nesvorný et al., 2012), Kepler-88 b (Nesvorný et al., 2013a), and Kepler-448 b and Kepler-693 b (Masuda, 2017).

Kepler-88, for example, shows TTVs of  $\sim 12$  h amplitude, attributed to a non-transiting planet c near the 2:1 mean motion resonance. Planet c was subsequently confirmed by radial velocity measures (Barros et al., 2014b), making it the first non-transiting exoplanet discovered by TTV to be confirmed in this way.

Although most systems characterised by TTVs are too faint for radial velocity measurements, a few have been verified or analysed through both approaches.

These include Kepler-18 (Cochran et al., 2011); Kepler-19 (Ballard et al., 2011b; Malavolta et al., 2017); Kepler-89 (Weiss et al., 2013; Masuda et al., 2013); and K2-19 (Narita et al., 2015b; Barros et al., 2015; Dai et al., 2016).

**Co-planarity** Using TTVs of single-planet systems to probe the population of non-transiting planets offers a promising way of determining the frequency of non-coplanar systems. TTVs have also been used to measure the co-planarity of systems with known stellar obliquities (Sanchis-Ojeda et al., 2012; Huber et al., 2013a). The subject is considered further in Section 6.30.5.

### 6.20.8 Absence of transit timing variations

In cases where there is no clear evidence for TTVs, timing data can be used to place limits on the mass of any hypothetical second planet. Such analyses have been made, for example, for GJ 1214 b (Carter et al., 2011c), and for Kepler-17 b (Désert et al., 2011b).

Figure 6.86 shows constraints on the perturber mass as a function of period ratio for Kepler-17 b (Désert et al., 2011b). Mass constraints on the perturber are more restrictive near mean motion resonances, and particularly restrictive for low-order resonances, especially for the interior and exterior 2:1 resonances. As an example, a Mars-mass perturber at the interior 2:1 resonance would have induced detectable TTVs.

For transiting systems in which little or no TTV signal is observed, but in which radial velocity observations suggest the existence of an additional planet (e.g., GJ 436 and HAT-P-13), Payne et al. (2010) suggested that retrograde orbits (§6.20.2) may provide an explanation.

### 6.20.9 Effect on transit search algorithms

Garcia-Melendo & López-Morales (2011) showed that transiting planets with significant TTVs can be systematically overlooked, or catalogued as false-positives, by transit search algorithms, unless they are in multi-planet transiting systems. They suggested that such a detection bias could explain the differences in the observed frequency of multiple systems among planets detected via transits, and those detected via other techniques.

### 6.20.10 Transit duration variations

**Causes of transit duration variations** Transits may also change in duration over time. Such *transit duration variations*, or TDVs, can originate from apsidal precession (§6.19.4; Pál & Kocsis, 2008; Damiani & Lanza, 2011), nodal precession (§6.19.5; Miralda-Escudé, 2002; Damiani & Lanza, 2011), as well as from perturbations from exomoons (Kipping, 2009a) or other planets in the system (Nesvorný et al., 2013a).

Effects of apsidal and nodal precession on the transit duration,  $t_T$ , are given by (Damiani & Lanza, 2011)

$$\dot{t}_T \propto b^2 \tan i \left\langle \frac{di}{dt} \right\rangle + (2b^2 - R_*^2) \frac{e \cos \omega}{1 + e \sin \omega} \left\langle \frac{d\omega}{dt} \right\rangle, \quad (6.143)$$

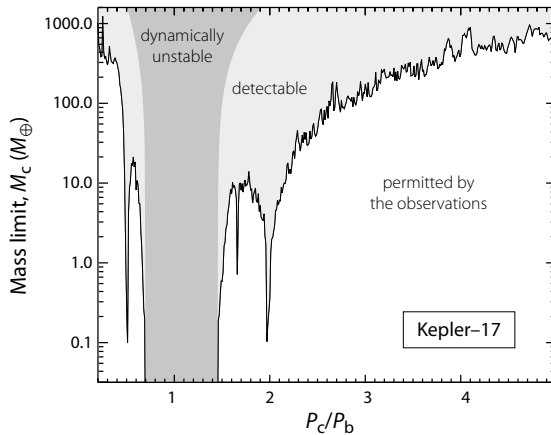


Figure 6.86: Upper mass limits for a hypothetical perturber as a function of perturber period, normalised to the period of Kepler-17b,  $P_c/P_b$  ( $P_b = 1.48$  d). The dark grey zone corresponds to the region of dynamical instability, the white zone corresponds to the region where the presence of a companion with a minimum mass would be permitted by the current limits on transit time variations. From Désert et al. (2011b, Figure 8), by permission of IOP Publishing/AAS.

where  $b$  is the impact parameter. The first term is a result of nodal precession, which can lead to a change in transit duration without accompanying transit timing variations (Damiani & Lanza, 2011). The second term is a result of apsidal precession. This is non-zero only for an eccentric orbit, and produces anti-correlated TTVs for the transit and for the secondary eclipse.

#### Measured systems

*TrES-2*: changes in transit duration of 3 min over 2 yr (Mislis & Schmitt, 2009) were attributed to precessional effects in a grazing-transit system (§6.14.14).

*Kepler-13*: changes in transit duration and depth are consistent with a precessing gravity-darkened system (§6.14.3).

*PTFO 8-8695b*: the transit profiles are of unusual shape, and also distinctly different in shape and duration in the 2009 and 2010 observations (§6.19.5).

Lack of transit duration variations in Kepler-9 (Holman et al., 2010) and Kepler-11 (Lissauer et al., 2011a) place limits on their mutual inclinations of  $\lesssim 10^\circ$ .

## 6.21 Trojans

In a star-planet system, the locations of the 1:1 orbital resonances define the Lagrange L4/L5 points of the planet's orbit (see also box, page 74). These points are linearly stable if the planetary masses are small. Objects in such 1:1 orbital resonances are collectively known as *Trojans*. In the solar system, Trojans accompany Mars, Jupiter, Neptune, and Uranus, with one also known accompanying Earth (§12.5.11). The specific case of circular orbits is a subset of more general 1:1 resonance orbits in which the semi-major axes are almost equal, while their eccentricities and orbits can take different values.

**Stability** The stability of the L4/L5 locations has traditionally been derived in the context of the restricted three-body problem, in which the Trojan is assumed to have zero mass. This results in the stability constraint that the Trojan should have less than  $\sim 4\%$  of the system mass (e.g. Murray & Dermott, 2000), which corresponds to  $M_p \sim 40M_J$  for  $M_\star = 1M_\odot$ . In the solar system, the largest Trojans have  $R_t \sim 100$  km (e.g. Jewitt et al., 2000; Fernández et al., 2003) and, in the case of the Jovian Trojans, a rather broad distribution of inclinations, up to  $\sim 30^\circ$  from Jupiter's orbital plane (Jewitt et al., 2000).

**Detailed configurations** Laughlin & Chambers (2002) assessed the system stability if the Trojan and planet have equal masses, corresponding to a resonant planet pair, and found that the relevant stability criterion is that sum of their masses is less than  $\sim 4\%$  of the system mass. This implies that the distribution of mass between planet and Trojan is irrelevant, and that stability does not prevent Trojans from being as massive as Earth or Jupiter in other systems.

New asymmetric solutions were found by Giuppone et al. (2010), which they termed *anti-Lagrange*. For small  $e$ , they are located at  $(\Delta\lambda = \pm 60^\circ, \Delta\omega = \pm 120^\circ)$ , where  $\Delta\lambda$  is the difference in mean longitudes, and  $\Delta\omega$  is the difference in longitudes of pericentre. They are still equilibrium solutions in the reduced average formalism, but quasi-periodic with two fundamental frequencies for the non-averaged problem in the inertial reference frame. Formally, both (Lagrange and anti-Lagrange) families comprise a 1-parameter family of stable fixed points, parametrised by  $e$  (Robutel & Pousse, 2013). As  $e$  increases, the stability regions become smaller, with the Lagrangian configuration being the first to vanish.

Inclined Trojan-like orbits, in both single and binary star systems, could be stable up to inclinations  $i \sim 60^\circ$ , with the structure of the stability regions closely connected with secondary resonances between the libration frequencies (Schwarz et al., 2012; Kovács, 2013; Páez & Efthymiopoulos, 2015).

The analytical Hamiltonian formalism of Robutel & Pousse (2013) recovers both Lagrange and anti-Lagrange families, as well as others such as the elliptic Eulerian Lagrangian configurations. Related families were studied by Hadjidemetriou et al. (2009); Hadjidemetriou & Voyatzis (2011). They classified these general orbits as belonging to a 'planetary branch', with the two planets moving in nearly Keplerian orbits with  $e \neq 0$ , and a 'satellite branch', where the gravitational interaction between the two planets dominates the attraction from the star, and the two planets form a close binary which revolves around the star. Starting with a 1:1 resonant planetary system with large eccentricities and subject to drag forces, the system can migrate along the family of periodic orbits and is finally trapped in a satellite orbit, providing another mechanism for the generation of a satellite system.

Various manifestations of 'exchange orbits', as in the Janus-Epimetheus system (see also box, page 74), have also been considered (Funk et al., 2011b, 2013; Bengochea et al., 2015).

**Formation and existence** Trojans may be a frequent by-product of planet formation, either formed *in situ* from the protoplanetary disk and surviving through inward migration (Laughlin & Chambers, 2002; Chiang & Lithwick, 2005), or from various capture mechanisms (Chiang & Lithwick, 2005; Morbidelli et al., 2005). In

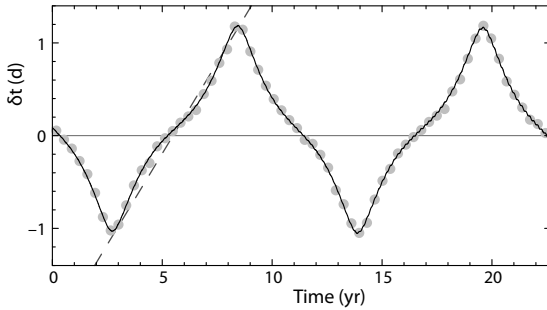


Figure 6.87: Transit timing variations for a planet in a 1:1 mean motion resonance horseshoe orbit. Grey circles are the TTVs from direct numerical integration (Vokrouhlický & Nesvorný 2014, eqn 1–2). The solid line is from semi-analytic theory (their eqn 40). Dashed inclined lines are from the expected amplitude of change in longitude rate during the switches between legs in the co-orbital cycle. From Vokrouhlický & Nesvorný (2014, Figure 3), by permission of IOP Publishing/AAS.

theory, they may reach Trojan/planet mass ratios much larger than the  $\leq 7 \times 10^{-9}$  of the solar system, perhaps as large as unity (Laughlin & Chambers, 2002). Terrestrial mass Trojans of giant planets in the habitable zone have been hypothesised (Dvorak et al., 2004b; Ji et al., 2005; Schwarz et al., 2005).

While some studies have examined the possibility of Trojans existing in known planetary systems, none have so been discovered (e.g. Goździewski & Konacki, 2006; Ford & Gaudi, 2006; Madhusudhan & Winn, 2009),

### 6.21.1 Detection from transit timing variations

Trojans can librate significantly around their equilibrium points, leading to large transit timing variations. This topic is covered more generally in Section 6.20.

Ford & Gaudi (2006) showed that, given a large-enough libration amplitude, Trojans could be detected from dynamical measurements (radial velocity or astrometry), as well as from transit photometry or transit-timing measurements. They could also be detected from a (systematic) difference between the transit mid-time and that calculated from the radial velocity data alone, an effect that recurs at every transit with amplitude

$$\Delta t \approx \pm 37.5 \left( \frac{P}{3 \text{ d}} \right) \left( \frac{M_t}{10 M_\oplus} \right) \left( \frac{0.5 M_J}{M_p + M_t} \right) \text{ min}, \quad (6.144)$$

where  $M_t$  is the Trojan mass. They ruled out Trojan companions to HD 209458 b and HD 149026 b more massive than 13 and  $25 M_\oplus$  respectively. Madhusudhan & Winn (2009) extended the search to 25 systems, finding the most constraining limit of  $2.8 M_\oplus$  for GJ 436.

Co-orbital planets on *horseshoe orbits* (encompassing L3, L4 and L5) would yield a characteristic shape of the TTVs (Figure 6.87), allowing approximate constraints to be placed on the planetary masses and orbit

amplitude (Vokrouhlický & Nesvorný, 2014). Such orbits may be generally long lived (Čuk et al., 2012).

Haghighipour et al. (2013) studied the possibility of detecting Earth-mass and super-Earth Trojan planets using Kepler transit timing variations, considering the induced variations in the transit timings of a Jovian-type planet in a short period orbit, induced by an Earth-mass/super-Earth Trojan planet. They identified orbital configurations (most favourably super-Earth Trojans with slightly eccentric orbits around short-period Jovian-type planets with masses slightly smaller than Jupiter) for which the resulting TTVs would be within the detectable range of the long-cadence data, with amplitudes reaching a few hours.

**Systematic Kepler search** A systematic search for Trojans was carried out on part of the early Kepler data by Janson (2013), and a possible candidate, KOI-103.01, identified. However, no compelling Trojan body was found, despite a typical sensitivity down to Earth-size objects. At the same time, the search did not preclude their existence, since stable Trojans need not necessarily share the same orbital plane as the planet, and thus may not transit. Similarly, some of the existing KOIs could in principle be Trojans themselves, with a primary planet orbiting outside of the transiting plane.

**Combining transits and radial velocities** The method proposed by Ford & Gaudi (2006), described above, is sensitive to co-orbital planets with zero to moderate eccentricity, and any libration amplitude (from the Lagrangian equilibrium to horseshoe configurations).

For high eccentricity orbits, Leleu et al. (2017) showed that detection can be simplified, and that a co-orbital companion can be detected, by combining the mid-transit time with the stellar radial velocity data. The method requires a 5-parameter fit to the radial velocity data,  $v(t) = \gamma + K[(\alpha - 2c) \cos nt - \sin nt + c \cos 2nt + d \sin 2nt]$  (their equation 18). The dimensionless parameter  $\alpha \propto m_2/m_1$ , such that  $\alpha > 0$  indicates a candidate harbouring a co-orbital companion. Observation of the secondary eclipse reduces the number of free parameters to four.

Lillo-Box et al. (2018) reported the start of such a search, based on the archival radial velocities of 46 close-in ( $P < 5 \text{ d}$ ) transit planet hosts.

### 6.21.2 Detection from photometric signatures

The significant libration of Trojans around their equilibrium points may lead to large transit timing variations, which may be missed in many planet-search algorithms. But its signature may also be present in a photometric light curve as a set of quasi-periodic transits, with a mean period equal to that of the planet with which it shares a 1:1 resonance (Ford & Holman, 2007; Carter et al., 2012; Janson, 2013).

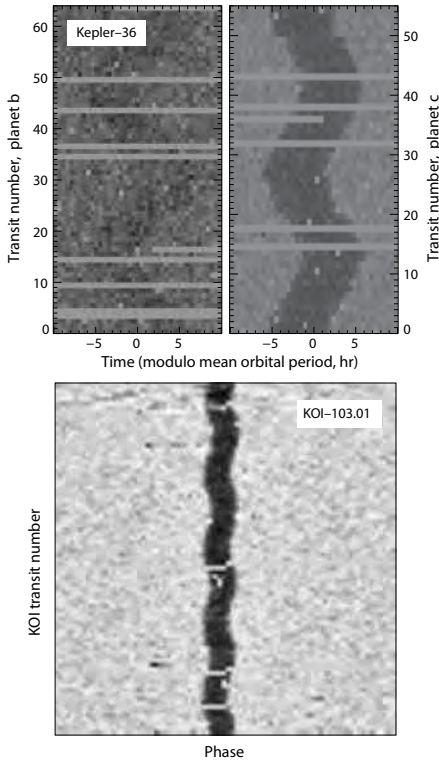


Figure 6.88: Examples of transit light curve ‘river diagrams’. Top: the 2-planet, 7:6 resonance system Kepler-36. Each row represents a transit interval, from the earliest (bottom) to the most recent (top). The abscissa is the time modulo the mean orbital period for planet b (left) and planet c (right). Grey scale pixels encode relative flux. Strictly periodic transits would produce a vertical shaded stripe, while the curved bands indicate transit time variations. From Carter et al. (2012, Figure 2), reprinted with permission from AAAS. Bottom: candidate from the Kepler Trojan planet search of Janson (2013), showing a section of the light curve centred on phase 0.0 for the quasi-periodic transits of KOI-103.01. Approximately sinusoidal transit time variations, with  $P_{\text{TTV}} = 261.7 \text{ d} \sim 17.6 P_{\text{orb}}$  (Mazeh et al., 2013), create a wiggled vertical trace. From Janson (2013, Figure 1), by permission of IOP Publishing/AAAS.

With respect to the planet orbit, a typical Trojan transit occur at phases near  $\phi_t = \pm\pi/3$  for trailing or leading orbits. The ephemeris will oscillate around these (Lagrange) points in a manner characterised by two superpositioned epicycles,  $\Omega_1$  and  $\Omega_2$  (Laughlin & Chambers, 2002), with periods that scale with the orbital period  $P_{\text{orb}}$ , but otherwise depend only on the masses, as

$$P_1 \sim P_{\text{orb}} \left[ 1 + \frac{27(M_{\text{p}} + M_{\text{t}})}{8(M_{\star} + M_{\text{p}} + M_{\text{t}})} \right], \quad (6.145)$$

$$P_2 \sim P_{\text{orb}} \left[ \frac{4(M_{\star} + M_{\text{p}} + M_{\text{t}})}{27(M_{\text{p}} + M_{\text{t}})} \right]^{\frac{1}{2}}, \quad (6.146)$$

where  $M_{\star}$  is the mass of the star,  $M_{\text{p}}$  the mass of the primary planet, and  $M_{\text{t}}$  the mass of the Trojan. Since

$M_{\star} \gg M_{\text{p}} + M_{\text{t}}$ , it follows that  $P_1$  is close to  $P_{\text{orb}}$ , and that  $P_2 \gg P_{\text{orb}}$ , typically by a factor of  $\sim 10$ – $100$  for realistic and potentially detectable planetary systems. The amplitude of  $\Omega_1$  is significantly smaller than that of  $\Omega_2$ , by a factor of  $\sim 25$ .

Janson (2013) searched for potential Trojan planet signals in all of the Kepler planet and candidate KOI data using both visual inspection, and an algorithmic search. For visual inspection, and as previously used in the analysis of quasi-periodic orbits (Carter et al., 2012; Carter & Agol, 2013), light curves are structured as a matrix-like *river diagram*, in which columns represent a specific phase with respect to a fixed orbital period, and each row is one such period. A transiting planet with a constant period will result a straight vertical band when folded at its period, whereas a quasi-periodic planet or Trojan will leave a more complex trace (Figure 6.88a).

Although various unusual features were detected (examples are KOI-187.01, KOI-193.01, KOI-2393.01, possibly attributable to highly eccentric planet orbits), no Trojan companions to the 2244 investigated KOIs were found, despite a typical sensitivity down to  $\sim 1 M_{\oplus}$ .

This does not fully exclude Trojans in this size range, since stable Trojans need not necessarily share the same orbital plane as the planet, and so may not transit. Such objects may be detectable in the full Kepler data, although requiring a substantial computational effort.

Hippke & Angerhausen (2015a) searched the entire Kepler data set for an average Trojan transit dip, ‘super-stacking’  $\sim 4000$  planets with a total of  $9 \times 10^4$  transits, providing upper limits to the average Trojan transiting area per planet, and with a possible Trojan-like signal in a sub-sample with  $P > 60 \text{ d}$ .

**Trojans masquerading as planets** Janson (2013) postulated that some KOIs may not be primary ‘planets’, but Trojan companions to a larger planet inclined to the line-of-sight, and not itself transiting. KOIs that show clear TTVs, but where no other transiting signal has yet been observed, may be considered as candidates. Janson (2013) propose KOI-103.01 as one such case, where significant TTVs with a period of 261.7 d (Mazeh et al., 2013) are accompanied by no other transiting planet (Figure 6.88b). If interpreted as epicyclic motion in a 1:1 resonance, the epicyclic period implies that the combined mass of the planet–Trojan system is  $150 M_{\oplus}$ .

Kepler-91, with a third dimming event  $60^\circ$  from the secondary eclipse, was considered as a Trojan candidate, but discounted due to the inferred high temperature (Placek et al., 2015).

## 6.22 Exomoons

Within the solar system, moons (both regular and irregular) represent a fundamental population, intimately related to its formation and evolution (§12.5.10).

**Terminology:** The terms *moon*, *exomoon*, and *satellite* are used here and in the literature somewhat interchangeably, and according to context. The subscript notation ‘s’ (for satellite) is used for properties such as their masses and radii, following Sartoretti & Schneider (1999).

The usual English proper name for Earth’s natural satellite is ‘the Moon’, although the Latin ‘Luna’ is occasionally used. As for the other names of individual astronomical objects (e.g. Sun and Earth), the IAU formally recommends capitalisation of the initial letters. The principal English adjectival form of the Moon is ‘lunar’, from the Latin. The less common *selenic*, from the Ancient Greek Selene, is the origin of the prefix ‘seleno-’ (as in selenography, study of its surface and physical features).

Naming conventions for the other solar system moons are detailed elsewhere (box, page 689).

From extrapolation of their observed frequency and inferred origin in the solar system, as well as through dedicated simulations (Elser et al., 2011), *exomoons* in other exoplanetary systems are considered to be ubiquitous, although none have been confirmed to date.

By analogy with inferred processes in the early solar system (§12.5.10), exomoons are likely to have formed through one of three main processes: as a by-product of planetary formation in a circumstellar disk, as a result of massive impacts, or through capture. Their longevity, due to tidal processes, is described in Section 10.11.4.

**Astrophysical interest** Interest in exomoons includes an understanding of their formation and survival. Such knowledge also has a direct bearing on the solar system, including, for example, understanding whether the disruptive formation of the Moon (§12.4) is likely to be a common event in other systems.

Interest in exomoons extends to their habitability, in part, again, through analogy with the solar system, in which Europa (J II), Titan (S VI), and Enceladus (S II) are considered to be plausible locations for some form of primitive biology (box, page 636). Habitability perspectives also embrace consideration of how exomoons might affect the habitability of the planets they orbit, for example, through their role in stabilising the host planet’s axial tilt.

**Dynamical stability** The stability of planetary satellites, specifically those in the solar system, has usually been studied by means of Hill surfaces, and there is an extensive literature (e.g. Szebeheley & Zare, 1977; Walker et al., 1980; Donnison & Williams, 1983; Donnison, 2009, 2010a; Li et al., 2010a; Lukyanov & Uralskaya, 2012).

For exomoons, stability studies have considered a variety of planet/moon mass ratios, as well as configurations applicable to transiting planets with the moon moving with a variety of eccentricities and inclinations (Donnison, 2010b, 2014). Even in dynamically-packed systems, including Kepler’s ‘systems with tightly-packed inner planets’ (§6.30.3), planets appear capable of sup-

porting dynamically stable satellites across a range of parameter space, only slightly decreased compared to that for single planets (Payne et al., 2013). In extreme cases, such as TRAPPIST-1, Hill radii and Roche radius considerations suggest they are absent (Kane, 2017).

Amongst a wide range of possible configurations, studies have examined: the stability of close-in exomoons in non-coplanar systems (Hong et al., 2015); effects due to planetary photoevaporation and the associated shrinking of their Hill sphere (Yang et al., 2016b); destabilisation through planet–planet scattering, with simulations suggesting an abundant Galactic population of free-floating (former) moons (Hong et al., 2018); trapping in compact mean motion resonance in accreting circumplanetary disks (Fujii et al., 2017b); the complicating dynamical behaviour of additional moons (Tarnopolski, 2017); effects on tidally induced migration (Alvarado-Montes et al., 2017); and misaligned moons from Lidov–Kozai oscillations (Grishin et al., 2018).

### 6.22.1 Detection methods

Several detection methods have been proposed, based on direct imaging, and from their transit signatures (and in principle from their phase curves). Perturbation of the planetary signal could also lead to their detection around radial velocity planets, microlensed planets (Han & Han, 2002; Han, 2008a), and pulsar planets (Lewis et al., 2008). In all cases, their small sizes and masses make their detection challenging.

**Imaging** With direct imaging and/or spectroscopy, various prospects for exomoon detection have been evaluated, including from the planet–moon barycentric motion (Cabrera & Schneider, 2007); through spectral detection of terrestrial moons in the CH<sub>4</sub> window of a host giant planet’s spectrum (Williams & Knacke, 2004); by detecting luminosity variations over a planetary year in the visual (Cabrera & Schneider, 2007) or (thermally-heated) infrared (Moskovitz et al., 2009; Moskovitz & Gaidos, 2011; Peters & Turner, 2013; Heller, 2016); by differences in the infrared flux at extreme phases, perhaps even in the case of an Earth–Moon system (Robinson, 2011); by their asymmetry-inducing polarisation signatures (Sengupta & Marley, 2016); or, with the next generation of extremely large telescopes, by albedo estimates of icy exomoons from their occultation light curves (Dobos et al., 2016).

**Transiting planets: overview** For transiting planets, moons (as well as planetary rings) should be detectable through their additional intensity decrement (Sartoretti & Schneider, 1999; Tusnski & Valio, 2011; Schneider et al., 2015), with the semi-major axis, eccentricity, and inclination angle around the host planet derivable from the transit curve observables, along with other constraints if a mutual (planet–exomoon) event occurs (Sato & Asada, 2009, 2010).



Exomoons may also be detectable through transit timing variations (Sartoretti & Schneider, 1999; Szabó et al., 2006; Kipping, 2009a,b; Lewis, 2013), through transit duration variations (Kipping, 2009a,b), through changes in the mean (Heller, 2014) and scatter (Simon et al., 2012a) in stacked light curves, and through perturbation in the Rossiter–McLaughlin transit signal (Simon et al., 2010). These are detailed further below.

**Effects on transit light curves** A satellite will distort a planet’s transit light curve, most notably affecting the symmetry of transit ingress and egress (Sartoretti & Schneider, 1999; Barnes & O’Brien, 2002; Domingos et al., 2006; Cabrera & Schneider, 2007; Sato & Asada, 2009; Kipping, 2011a,b; Heller, 2014). The more exacting detection via spectral contrast phase curves may be feasible in the future (Forgan, 2017).

The transit effect can be assessed as follows. The orbital radius of the planet’s satellite must lie, to first order, somewhere between the Roche radius (within which it will disintegrate due to the planet’s tidal forces exceeding its gravitational self-attraction) and the Hill radius (the gravitational sphere of influence of the planet in the proximity of the more massive host star, page 512). For rigid bodies the Roche radius is given by

$$R_R = R_p \left( \frac{2\rho_p}{\rho_s} \right)^{1/3}, \quad (6.147)$$

where  $\rho$  the density, and subscripts denote planet and satellite. In reality, the Roche radius depends on the body’s internal viscosity and tensile strength.

For HD 209458 b (with  $M_p \sin i = 0.69M_J$ ,  $M_\star = 1.01M_\odot$ ,  $a = 0.0468$  au)  $R_H \approx 4.2 \times 10^5$  km  $\approx 5.9R_J$ . With the planet’s orbital speed of  $\sim 140$  km s $^{-1}$ , transit features of a gravitationally bound object could lie as much as 49 min before or after the corresponding planet features, compared to the full transit duration of 184 min. A satellite might therefore be detectable from its own photometric transit signature significantly before or after the main transit. The transit duration could also differ from that of the planetary transit if it has significant orbital motion, or due to its different transit projection.

Weidner & Horne (2010) derived limits on the masses and orbits of exomoons around the transiting planets known at the time, based on their Hill stability as well as their dynamical orbit stability. For 92% of their sample of 87 planets, satellites larger than the Moon could typically be excluded, at least on prograde orbits. Retrograde moons could have larger maximal orbital radii and masses due to their much larger Hill radii.

**Light curve stacking** Phase-folding light curves using a linear ephemeris will lead to a moon appearing at different phases at each epoch. However, the fact that it is constrained to lie within the planet’s Hill sphere this imparts some quasi-coherent properties into the phase-folded light curve. Simon et al. (2012a) showed that this

quasi-coherence will lead to an increase in the photometric scatter, their *scatter peak*, in the temporal region surrounding the planetary event.

A similar approach was discussed by Heller (2014); Heller et al. (2016a): due to the projection of a transiting exomoon orbit onto the celestial plane, the exomoon appears more often at larger separations from its host planet, resulting in a slight photometric decrease, or ‘shadowing’ in this temporal region. With a dozen or more randomly sampled observations, a photometric *orbital sampling effect* progressively appears in the phase-folded transit light curve, depending on the moon’s radius and planetary distance, with more complex structures appearing for multiple moons (Figure 6.89). Both transit timing variations and transit duration variations permit measurements of the moon’s mass. Heller (2014) estimated that moons as small as Ganymede may be detectable in the Kepler data, with M stars being the most promising hosts. Exomoons with a factor 10 larger mass can most likely be found in the Kepler data of K stars, including moons in the stellar habitable zone.

This was applied to a large ‘super-stacked’ sample of Kepler planets by Hippke (2015), who found a significant signal for planets with  $P_{\text{orb}} \sim 35\text{--}80$  d. This corresponds to an average dip per planet of  $6 \pm 2$  ppm, or  $R_s \sim 2120 \pm 350$  km for their  $\langle R_\star \rangle = 1.24R_\odot$ .

Teachey et al. (2018) also applied phase-folding, statistically, to a stacked sample of 284 viable moon-hosting Kepler planet candidates, ranging from Earth to Jupiter in size, and 0.1–1.0 au in separation, resulting in a ‘grand light curve’ with 5.1 ppm rms. They constrained the occurrence of Galilean-analogue moon systems to  $\eta < 0.38$ . A single-moon model of variable size and separation identified a slight preference for a population of ‘super-Io’ moons,  $0.5R_\oplus$  objects orbiting at  $5\text{--}10R_p$ . They also identified an exomoon candidate, Kepler-1625 b I (their Roman numeral designation following that for solar system satellites, cf. box, page 689). Analysis with a more complete photo-dynamical treatment (§6.22.2) suggests a  $10M_J$  planet with a Neptune-sized moon orbiting at  $a_s = 19.1 \pm 2R_p$ , well outside the Roche radius, and within the planet’s Hill sphere (Figure 6.90). HST observations are scheduled.

**Transit times and durations** Various studies have considered the detectability of exomoons from transit time variations (Sartoretti & Schneider, 1999; Deeg, 2002; Arnold, 2005b; Schneider, 2005; Szabó et al., 2006; Simon et al., 2007; Kipping, 2009a,b; Kipping et al., 2009; Heller et al., 2016b).

For a circular satellite orbit, the displacement of the planet with respect to the planet–satellite barycentre is

$$\delta\alpha = a_s \frac{M_s}{M_p}, \quad (6.148)$$

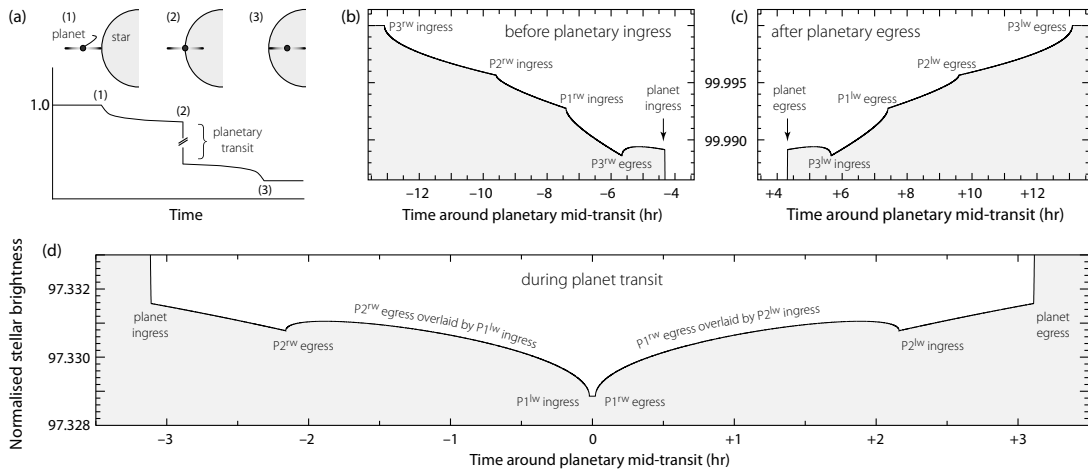


Figure 6.89: Photometric ‘optical sampling effect’ in multiple phase-folded transits, caused by an orbiting exomoon. (a) during ingress, at epoch 1, the satellite’s probability distribution along its circumplanetary orbit (denoted by the grey scale; ‘lw’ and ‘rw’ refer to its left and right wings) touches the stellar disk, from then on causing a small but steep decline in stellar brightness. At epoch 2, the planet crosses the stellar disk. Thereafter, larger values of the probability distribution lead to a decreasing brightness until the exomoon orbits have completely entered the stellar disk at epochs 3; (b–d) the effect shown for a hypothetical 3-satellite system around a super-Jovian planet transiting a  $0.64R_{\odot}$  K star in the habitable zone. The radii of the satellites are (outer to inner) are  $0.86, 0.52$ , and  $0.62R_{\oplus}$ , assuming ice-to-mass fractions of the Galilean moons. A large number of transits has been averaged to obtain this (noise-free) curve. From Heller (2014, Figures 3 and 5), by permission of IOP Publishing/AAS.

where  $a_s, M_s$  are the satellite’s semi-major axis and mass. For circular co-planar orbits, the peak-to-peak time difference between the mid-transit point for the planet and system barycentre is then (Sartoretti & Schneider, 1999; Kipping, 2009a)

$$\Delta t \approx 2a_s \frac{M_s}{M_p} \frac{P}{2\pi a}, \quad (6.149)$$

where  $P, a$  are the planet’s period and orbital radius. For a  $1M_{\oplus}$  satellite orbiting HD 209458 b at a maximum distance of the Hill radius,  $R_H$ , the amplitude of the timing excursion about the mean orbital phase is 13 s, comparable to the standard error on the mid-time of a single transit (Brown et al., 2001).

Since the displacement is proportional to the product  $a_s M_s$ , determining  $M_s$  requires an independent knowledge of  $a_s$  (Ford & Holman, 2007). Estimating the satellite orbit period uniquely is impeded by the Nyquist-limited sampling imposed by the fundamental (transit) sampling rate of  $0.5P^{-1}$  (Kipping, 2009a).

Kipping (2009a) evaluated transit time variations and transit duration variations for a co-aligned planet–moon system at  $i = 90^\circ$ , and with non-zero eccentricity. To maintain Hill stability, the orbital frequency of any exomoon will always be higher than the (Kepler) sampling frequency, such that the orbital period cannot be reliably determined from the transit time variations, only a set of harmonic frequencies. The amplitude is  $\propto M_s a_s$  (Equation 6.149), again implying that  $M_s$  and  $a_s$  cannot be separately determined.

However, the amplitude of transit *duration* variations is also detectable, with two important advantages. First, the amplitude is  $M_s a_s^{-1/2}$ , such that the ratio of transit duration variations to transit time variations allows for  $M_s$  and  $a_s$  to be separately determined. Furthermore, the transit duration signal has a  $\pi/2$  phase difference to the transit time variations signal, making it an important complementary probe.

For three favourable cases, rms transit time and duration variations are {13.7, 12.6 s} for GJ 436 b, {7.7, 9.3 s} for CoRoT-4 b, and {4.6, 6.8 s} for HAT-P-1 b.

Kipping (2009b) considered the effect for the more general case of  $i \leq 90^\circ$  and an exomoon inclined from the planet–star plane. The resulting transit duration signal has two major components, one due to velocity variations (already noted by Kipping 2009b), and an additional component due to transit impact parameter variation. The two effects are additive for prograde orbits, and deductive for retrograde orbits, in principle yielding the sense of orbital motion. Results applied to Kepler-class photometry suggest that habitable zone satellites down to  $0.2M_{\oplus}$  could be detected (Kipping et al., 2009).

Szabó et al. (2013) identified a number of hot Jupiters that could be accompanied by exomoons on the basis of their large transit time scatter (their Figure 6).

**Modified Rossiter–McLaughlin effect** The amplitude and signature of the Rossiter–McLaughlin effect (§6.18) will be modified according to the planet–moon transit configuration (Simon et al., 2010; Zhuang et al., 2012),

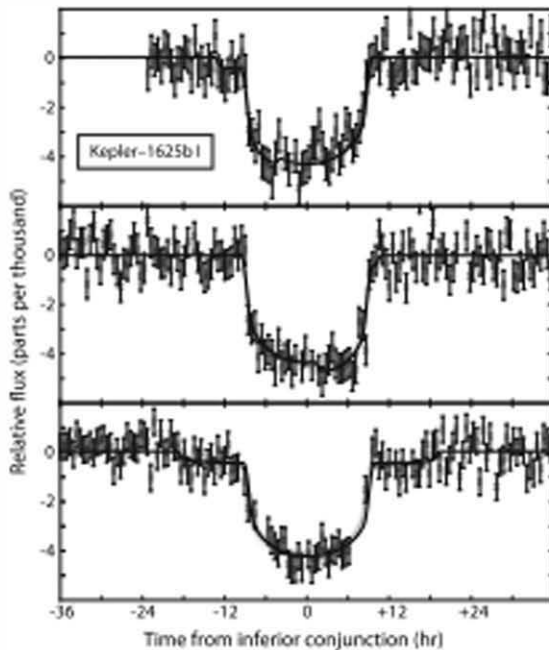


Figure 6.90: The three (Kepler) transits of the exomoon candidate Kepler-1625 b I, with 100 draws of model posteriors from the LUNA photo-dynamical fitting algorithm. The black dashed line is the maximum a posteriori model. From Teachey et al. (2018, Figure 1.3), by permission of RSP Publishing/AAS.

with expected amplitudes reaching tens of  $\text{ms}^{-1}$  (Figure 6.91). Such observations will provide constraints on the exomoon radius, in some cases on its orbital period and, if the transit time of the moon is known from transit photometry, the space orientation of its orbit. Combining its mass from transit photometry, with its radius from the Rossiter–McLaughlin effect, determination of its density,  $\rho_s$ , should also be possible.

### 6.22.2 Photo-dynamical treatment

A more complete *photo-dynamical* approach is employed by the ‘Hunt for Exomoons with Kepler’ (HEK), a survey for exomoons around transiting planets discovered by Kepler (Kipping et al., 2012a, 2013b.a, 2014b, 2015b). The aim is to model all aspects of the transit photometric and timing signals, simultaneously and self-consistently, accordingly embracing all effects on light curves and transit times noted in Section 6.22.1.

In this photo-dynamical treatment, observations are compared to a Bayesian prior, based on a dynamical star–planet–exomoon model. Specifically, searches are made for photometric transits of an exomoon, as well for the timing perturbations induced by its mass. For each time step, the underlying dynamical model, LUNA (Kipping, 2011a), calculates the sky-projected positions of the planet and putative exomoon relative to the star (using a nested Keplerian adjustment). Based on these pre-

dicted positions, the fraction of star light blocked by the planet and the moon are calculated. Effects modeled include stellar limb darkening using a quadratic law (Kipping, 2013a), and long-cadence smearing accounted for by appropriate re-sampling (Kipping, 2010a).

The parameter space explored by LUNA is complex, multimodal, and degenerate. While in principle embracing the other search methods, it does so with a corresponding computational burden: Kipping et al. (2015b) report a mean of 33 000 h CPU per KOI.

The series of (HEK) papers covers a total of 51 KOIs: methodology (Kipping et al., 2012a, paper I); treatment of 7 single KOIs (Kipping et al., 2013b, paper II); search for the habitable-zone Kepler-22 b (Kipping et al., 2013a, paper III); a sample of eight M dwarf host stars (Kipping et al., 2014b, paper IV); and a further sample of 41 KOIs (Kipping et al., 2015b, paper V).

For the ensemble of studies, Kipping et al. (2015b) find no compelling evidence for exomoons, although 13 KOIs yield spurious detections driven by instrumental artefacts, stellar activity and/or perturbations from unseen bodies. Concerning the former, correlated noise structure is a particularly frequent source of exomoon transit false-positives, as in the case of Kepler-90 g (Kipping et al., 2015a), and perhaps in their case of Kepler-86 b = H4-2 b. They find 7 KOIs exhibiting evidence of transit timing variations suggestive of additional planets, including Kepler-10 c.

Statistically, and in terms of the experimental limits on mass ratios, the approach is sensitive to Charon–Pluto mass ratios (0.12) for ~47% of cases, and to Moon–Earth mass ratios (0.012) for ~15%. Transforming to absolute masses using the estimated transiting planet mass, the method probes down to  $0.04 M_{\oplus}$ , with a sensitivity to Earth-mass moons for 40% of cases, and to the smallest moons capable of sustaining an Earth-like atmosphere ( $0.3 M_{\oplus}$ ) for 30% (Figure 6.92).

They argue that had they searched for the photometric transit signals of exomoons alone, rather than using photodynamics, some 25% of KOIs would have erroneously been concluded to harbour exomoons due to residual time correlated noise in the Kepler data.

By-products of the study are planet discoveries from transit timing variations (Nesvorný et al., 2012, 2013a).

**Derivation of planet mass and density** For a transiting exoplanet accompanied by a moon which also transits, the absolute masses and radii of the star, planet and moon can be determined (Kipping, 2010b). For a planet–star system,  $M_p$  can be determined from the light curve by the application of Kepler’s third law (Equation 6.31). In an analogous way, the density of the planet,  $\rho_p$ , can be determined for a planet–moon system which transits a star, and thus their density ratio is known.

Combining this with the observed ratio of radii, and radial velocity measurements, absolute star and planet

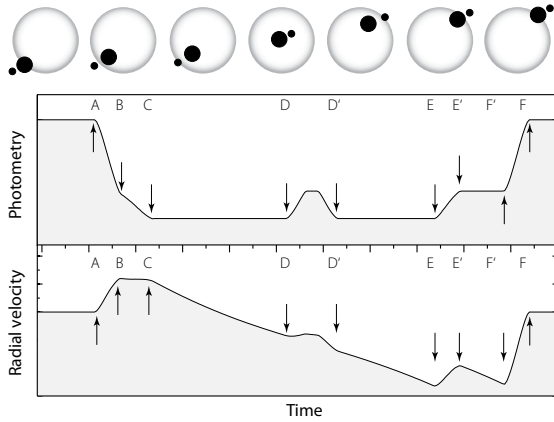


Figure 6.91: Schematic of a transiting planet–exomoon system, showing the difference stages in the transit (top), the associated transit photometry (middle), and the stellar radial velocity anomaly (bottom). At the start of the transit (A) the planet starts to block the stellar light, followed by the exomoon (B), until both occult the stellar disk (C). The bulge (D–D′) occurs if there is a mutual planet–moon eclipse. Similar stages accompany the progressive egress of the system (E–F). From Zhuang et al. (2012, Figures 2–3), by permission of IOP Publishing/AAS.

dimensions can be determined. Combining the moon’s radius with its mass, determined through the dynamical effects of transit timing variations, would lead to knowledge of its density, and constraints on its composition.

In summary, for a transiting planet–moon system, accurate solutions for  $R_\star$ ,  $M_\star$ ,  $R_p$ ,  $M_p$ ,  $R_s$ , and  $M_s$  can be obtained if dynamical effects (transit time or duration variations) are detectable. If dynamical effects are not detected, approximate solutions for all parameters can be obtained on the assumption  $M_s \ll M_p$ , except for  $M_s$  where only an upper limit can be assigned.

Kipping (2010b) gives the densities of the planet, satellite and star in terms of observables as

$$\rho_p = \frac{3\pi(a_s/R_\star)^3 (1 + [M_s/M_p])^2}{GP_s^2(R_p/R_\star)^3}, \quad (6.150)$$

$$\rho_s = \frac{3\pi(a_s/R_\star)^3 (1 + [M_s/M_p])^2 (M_s/M_p)}{GP_s^2(R_s/R_\star)^3}, \quad (6.151)$$

$$\rho_\star = \frac{3\pi}{G} \left[ \frac{(a_b/R_\star)^3}{P_b^2} - \frac{(a_s/R_\star)^3 (1 + [M_s/M_p])^3}{P_s^2} \right], \quad (6.152)$$

where  $a_s$  and  $P_s$  are the semi-major axis and period of the moon around the planet–moon barycentre,  $a_b$  and  $P_b$  are the semi-major axis and period of the planet–moon barycentre around the star, and the mass ratio  $M_s/M_p$  is directly determinable from timing effects.

The associated determination of  $M_\star$  and  $R_\star$  (Kipping, 2010b, Equations 12 and 14) could provide further constraints for stellar evolution models.

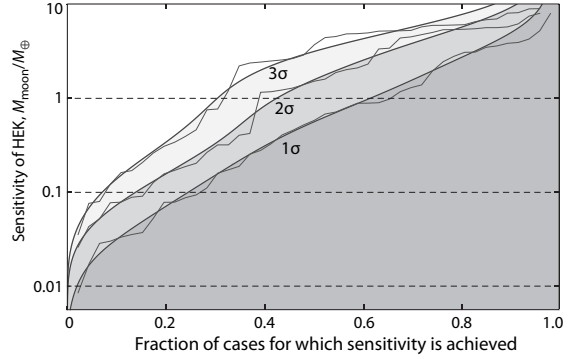


Figure 6.92: Sensitivity of the ‘Hunt for Exomoons with Kepler’ (HEK) photo-dynamical survey to the moon/planet mass ratio, based on 46 null results (thin lines) from 57 KOIs, and transformed to absolute masses via estimates of  $M_p$ . HEK is sensitive to  $1M_\oplus$  for 40% of cases, and to  $0.3M_\oplus$  for 30%. From Kipping et al. (2015b, Figure 7), by permission of IOP Publishing/AAS.

### 6.2.2.3 Sense of orbital motion

The distinction between prograde and retrograde satellite orbits will be an important diagnostic of their formation (see §12.5.10). Various approaches for distinguishing between them have been suggested.

Assuming some knowledge of the planet’s orbital orientation (e.g. through radial velocity or astrometry), approaches include measuring the Doppler shift of the planet’s spectrum due to motion about the planet–moon barycentre, detection of perturbations in the position of the planet–moon photocentre (Cabrera & Schneider, 2007), and exploiting mutual events in the infrared or optical to distinguish between a planet passing in front of a moon and *vice versa* (Cabrera & Schneider, 2007).

Lewis & Fujii (2014) argued that most methods cannot distinguish prograde and retrograde orbits. For transit searches, a distinction is only feasible when there is a dynamical evolution of the orbit (e.g. due to 3-body effects), resulting in different relations between transit times and durations (§6.22.2).

Heller & Albrecht (2014) identified an effect which relies on mutual planet–moon events during a stellar transit, along the lines observed by Hirano et al. (2012a) for Kepler–89 (§6.14.16). Eclipses with the moon passing *behind* the planet will be late with regard to the moon’s mean orbital period (and will be early when the moon passes in *front* of the planet) due to the finite speed of light, resulting in what they refer to as a *transit timing dichotomy*. For the ten largest moons in the solar system, this is between 2–12 s, suggesting that Earth-sized moons around nearby exoplanets could be measured by the E–ELT.

Heller & Albrecht (2014) also identified a method based on distortions in the infrared spectrum of a rotating giant planet transited by a moon. The Rossiter–McLaughlin effect in the planetary spectrum is sensitive to the angle between the planet’s equator and the moon’s circumplanetary orbital plane, and to the moon’s sense of orbital motion with respect to the planet’s rotation. A large moon transiting an imaged planet like  $\beta$  Pic b would result in a Rossiter–McLaughlin amplitude of almost  $100 \text{ m s}^{-1}$ , about twice that of HD 209458 b.

A distinction between prograde and retrograde orbits may also be possible in cases where demonstrable dynamical instability of the prograde solution implies that the orbit must be retrograde (Lewis & Fujii, 2014).

### 6.22.4 Other considerations

**Detection through plasma tori** Early ingress (ultra-violet) transit signatures attributed to planetary Roche lobe overflow, or bow shocks, have been observed in WASP-12 b and HD 189733 b (§6.14.10). An alternative explanation due to a plasma torus associated with an exomoon was proposed by Ben-Jaffel & Ballester (2014), and developed by Noyola et al. (2016).

The concept of a plasma torus relies on a small volcanic satellite, like Io, orbiting a main body and loading a substantial mass of plasma to its magnetosphere, as a result of both strong tidal effects and the substantial heating from the stellar insolation. Specifically, a small rocky body orbiting the planet will suffer significant tidal effects from both the planet and the nearby star, resulting in volcanic activity and plasma outflow (Schaefer & Fegley, 2004; Kaltenecker et al., 2010b; Ben-Jaffel & Ballester, 2014). Despite the small size of a moon, the spatial extent of its associated plasma torus can be large enough to produce substantial transit absorptions.

For HD 189733 b, an exomoon transiting  $\sim 16R_p$  ahead of the planet and ejecting  $\sim 10^{29}$  C II ions  $s^{-1}$  has been invoked to explain the observed early ingress absorption (Ben-Jaffel & Ballester, 2014). For WASP-12 b, a moon transiting  $\sim 6R_p$  ahead of the planet and ejecting  $\sim 10^{28}$  Mg II ions  $s^{-1}$  is required to explain the near ultraviolet early ingress absorption feature (Figure 6.93).

An alternative source could be outgassing from the molten surface of Trojan satellites on tadpole orbits near the Lagrange points L4 and L5 (Kislyakova et al., 2016).

**Detection from radio emission** In the Jupiter-Io system, Io's motion produces currents along the field lines that connect it to Jupiter's polar regions. The currents generate and modulate radio emission along their paths via electron-cyclotron maser instability (Crary, 1997). Such modulation of planetary radio emission may reveal exomoons around giant planets such as  $\epsilon$  Eri and GJ 876 (Noyola et al., 2014, 2016; Weber et al., 2017).

**Habitability** Various studies have considered exomoon habitability, including effects of illumination, tidal locking, tidal heating, and outgassing (box, page 627). The detectability of habitable exomoons from transit time and transit duration variations with Kepler has been considered by Awiphan & Kerins (2013).

### 6.22.5 Searches and candidates

In addition to the exomoon searches noted in this section, transit light curve signatures have been searched for without success in HST observations of HD 209458 b (Brown et al., 2001). Similar observations of HD 189733 b excluded  $1M_{\oplus}$  satellites around it (Pont et al., 2007a).

Searches have also been made for high-frequency transit time variations in hot Jupiter systems (Szabó

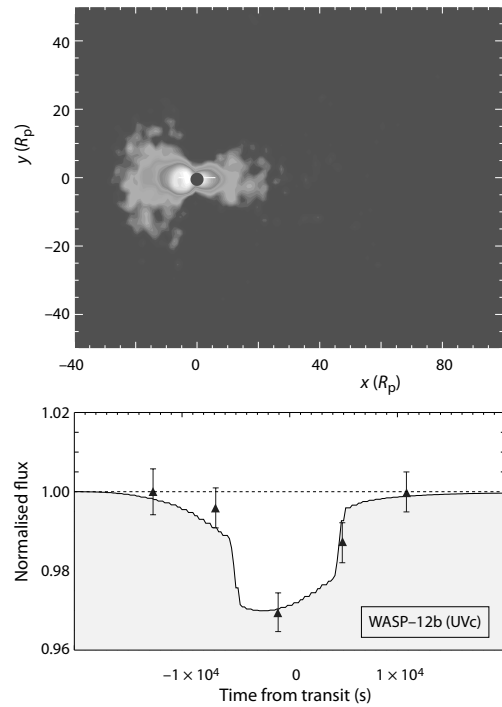


Figure 6.93: Top: 3d 'particle-in-cell' simulation of an exomoon plasma torus evolving within the magnetospheric cavity of WASP-12 b (relative stellar wind speed of  $230 \text{ km s}^{-1}$ ), showing the distribution of Mg II ions in the meridional plane. The satellite is orbiting at  $6R_p$  from the planet (orbit shown by the horizontal white line), and losing Mg II ion plasma at a rate of  $500 \text{ kg s}^{-1}$ . Bottom: fit to the WASP-12 b Mg II light curve, obtained from HST-COS UVC observations by Fossati et al. (2010b), again corresponding to a moon at  $6R_p$  from WASP-12 b, losing Mg II ions at  $500 \text{ kg s}^{-1}$ . From Ben-Jaffel & Ballester (2014, Figures 2b and 3), by permission of IOP Publishing/AAS.

et al., 2013). Of the 36 systems with significant transit time variations, not explained by stellar rotation, activity, or sampling, Szabó et al. (2013) suggested that three may host multiple planets or possibly moons: Kepler-485, Kepler-718, and KOI-977.

From their detailed photo-dynamical treatment (§6.22.2), Kipping et al. (2015b) found no compelling exomoon. A candidate identified through light curve stacking, Kepler-1625 b, is supported by the more detailed photo-dynamical analysis (Teachey et al., 2018).

One explanation for the non-detection of exomoons, at least around hot Jupiters, is that their small Hill radii may limit their satellite population to bodies captured after planet formation (Domingos et al., 2006; Namouni, 2010; Weidner & Horne, 2010; Kane et al., 2013b).

Transit detection limits with CHEOPS correspond roughly to the Earth-Moon system (Simon et al., 2015a).

**Exomoon candidates** A small number of exomoon candidates have been noted previously in this section, or elsewhere in this volume. To summarise:

**Exocomets:** In the solar system, comets are small icy bodies, remnants of its early formation, that display a coma on close approach to the Sun. Trillions are inferred to exist beyond the orbit of Neptune, in the Kuiper belt and Oort cloud (§12.5.7).

Beyond the solar system, the more general association of infalling bodies with planetary formation was suggested by Lagrange et al. (1987). Dynamical modeling showed that large numbers would be perturbed into moderately eccentric orbits towards the parent star (Beust et al., 1990; Beust & Morbidelli, 1996). It is plausible that the evolution of all young systems is punctuated by brief but violent episodes of instability as terrestrial planetesimals reach diameters of ~1000 km, and perturb the orbits of the smaller bodies (e.g. Kenyon & Bromley, 2001; Rieke et al., 2005).

In young or debris-rich systems with large planets still forming, gaseous comae and tails may be common (Zuckerman & Song, 2012; Welsh & Montgomery, 2013). The search for *exocomets* has therefore focused on young (< 50 Myr) A-type stars, potentially hosting young planetary systems which may be relatively rich in comet-like debris. The first surveys found that 25% of all rapidly rotating A-stars are surrounded by gas, largely confined to disks (Abt et al., 1997). Subsequent studies found that 30% of normal A-type stars exhibit infrared excesses due to debris dust disks (Su et al., 2006; Morales et al., 2011). Over a broad range of spectral types (B8–M0), dust production appears to occur just inside the snow line ( $T \sim 170 - 190$  K), suggesting that at least some arises from the sublimation of icy bodies (Morales et al., 2011; Su et al., 2013).

The high luminosity of A-type stars is such that their radiation pressure removes dust particles from their disks on time scales  $\ll 1$  Myr. Thus, the dust (and gas) in the debris disks that surround some main sequence A stars is unlikely to be primordial, but rather constantly re-supplied by the collision and evaporation events amongst (asteroid and comet-like) planetesimals (Kenyon & Bromley, 2004a).

*Discovery by spectroscopy:* Absorption by circumstellar gas around A stars has been probed by Ca II K-line spectroscopy at 393.3 nm (Lagrange-Henri et al., 1990b; Welsh et al., 1998; Redfield et al., 2007; Montgomery & Welsh, 2012). Variability over hours or days was first detected in  $\beta$  Pic (Ferlet et al., 1987; Lagrange-Henri et al., 1990b), and subsequently confirmed in the ultraviolet (Vidal-Madjar et al., 1994). Transient blueshifted absorption (Crawford et al., 1998) is outnumbered by redshifted events by a factor 10 (Lagrange-Henri et al., 1992). Rapid variability in the Ca II infrared triplet at 854 nm suggests that most of the ionised calcium was formed less than 1 au from the star (Hobbs et al., 1988). The presence of molecules with short residence times, in particular CO, demonstrates that at least some of the gas is produced through the evaporation of frozen bodies, with the CO gas close to its sublimation temperature of ~25 K (Lecavelier des Etangs et al., 2001).

Short-term absorption variability in  $\beta$  Pic is now attributed to gas vaporised from km-sized *falling evaporating bodies*, or exocomets, that have been perturbed by an outer planet into star-grazing orbits (Beust et al., 1990). Further evidence was provided when  $\beta$  Pic b was imaged with roughly the predicted mass and separation (Lagrange et al., 2009a). Events are believed to be triggered by mean motion resonance with a planet on a moderately eccentric orbit (Beust & Morbidelli, 1996). Spectroscopy of hundreds of transit events now suggests two cometary families, with distinct distributions of their longitudes of pericentre, compatible with trapping in mean motion resonance with a massive planet (Kiefer et al., 2014b).

Similar transient absorption features attributed to exocomets have since been observed in several other systems, including (chronologically) HR 10 (Lagrange-Henri et al., 1990a); 2 And (Cheng et al., 1997; Montgomery & Welsh, 2012); HD 85905 (Welsh et al., 1998; Redfield et al., 2007); 49 Cet (HD 9672) and 5 Vul (HD 182919) (Montgomery & Welsh, 2012); HD 21620, HD 110411, HD 145964 and HD 183324 (Welsh & Montgomery, 2013); HD 172555 (Kiefer et al., 2014a);  $\phi$  Leo (particularly pronounced; Eiroa et al., 2016). and HD 24966, HD 38056, HD 79469, HD 225200 (Welsh & Montgomery, 2018).

Systems in which ongoing episodes analogous to the solar system's Late Heavy Bombardment (box, page 669), inferred from the disk geometry and infrared emission, include  $\eta$  Cor (Lisse et al., 2012), and KIC-8462852 (Lisse et al., 2015, §6.23).

*Kepler-485, Kepler-718, and KOI-977:* proposed as exomoon candidates due to their photometric transit scatter (Szabó et al., 2013).

*Kepler-1625b:* proposed as an exomoon candidate due to its photometric transit scatter (Teachey et al., 2018).

*ISWASP J1407:* has a structured ring system that has been attributed to exomoons orbiting the secondary (§6.14.6, van Werkhoven et al., 2014b).

*MOA-2011-BLG-262:* proposed as a microlensing candidate for a free-floating exoplanet-exomoon system (box, page 145).

### 6.23 Exocomets

Comets in the solar system are described in Section 12.5.7. Evidence for the existence of comets in exoplanetary systems, or *exocomets*, and their discovery by spectroscopy, is given in the accompanying box

(page 282). The following focuses on their expected transit signatures, and candidates so far reported.

**Transit signatures** Lecavelier des Etangs et al. (1999) performed numerical simulations of stellar occultations by extrasolar cometary tails, finding that such *exocomets* should present a characteristically 'rounded triangular' profile in transit surveys, typically achromatic. For a high-accuracy photometric survey of several tens of thousand of stars, they predicted the possible detection of several hundred occultations per year.

Simulations using a geometrical model of the dust distribution, and optical properties of cometary grains, such as those inferred from the photometric variations for  $\beta$  Pic (box, page 282), suggest that the detection of comets might be possible with transit accuracies of  $10^{-4}$ ; they are predicted to give a 'rounded triangular' shape, largely achromatic, as a typical transit signature (Lecavelier des Etangs et al., 1997, 1999).

Other simulations of the expected occurrence and

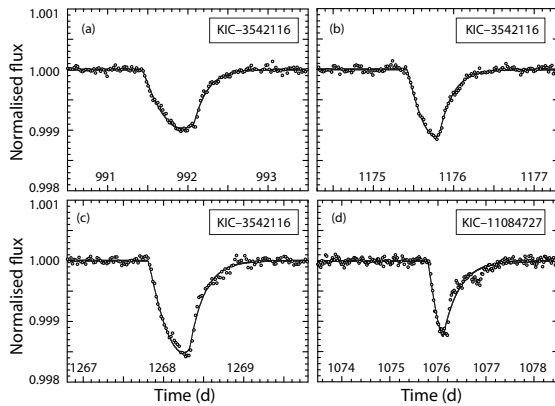


Figure 6.94: Exocomet candidates: (a–c) Kepler photometry (and model fits) covering 3 d around each of the three larger exocomet-like transits in KIC-3542116; (d) the similar exocomet-like dip feature in KIC-11084727. From Rappaport et al. (2018b, Figures 3 and 13), © Oxford University Press.

detectability of exocomets have been made (e.g. Loibnegger et al., 2017; Wyatt et al., 2017).

**Candidates** While KIC-8462852 (Boyajian’s star) was initially considered possibly explicable in terms of comets, a break-up (disintegrating) event seems more likely. The system is described further in Section 6.14.22.

KIC-3542116, discovered from a visual search of the entire Kepler data set, shows distinct asymmetric transits with a steeper ingress and shallower egress that can be ascribed to objects with a trailing dust tail passing over the stellar disk (Rappaport et al., 2018b). There are three transits with depths of 0.1% that last for about one day (Figure 6.94a–c), and three that are shallower and of shorter duration. A dust-tail model suggests a transverse comet speed of 35–50 km s<sup>-1</sup>, a minimum dust mass in the tail of 10<sup>13</sup> kg, and an implied total comet mass of 3 × 10<sup>14</sup> kg, about that of Halley’s comet.

Rappaport et al. (2018b) also report the discovery of a single comet-shaped transit in KIC-11084727 with similar transit and host star properties (Figure 6.94d).

**Exo-asteroids** In addition to the extended transit signatures (possibly) attributed to exocomets, disintegrating planets (§6.14.22), and various dust structures in transition disks and debris disks more generally (§6.14.6), at least one feature has been (possibly) attributed explicitly to an asteroid belt.

A subset of the intermediate mass Herbig Ae stars called UXOr variables, after their prototype UX Ori, show irregular variability at optical wavelengths, attributed to changing column densities of intervening dust causing variable extinction. Amongst these, erratic variability and large infrared excess in the young solar-like star RZ Psc has been considered as a possible asteroid belt (Kennedy et al., 2017), or the recent destruction of one or more massive orbiting bodies (Punzi et al., 2018).

## 6.24 Transit and eclipse spectroscopy

This section covers the basic principles of transit and eclipse spectroscopy, setting out the configurations and observables for the primary transit, the secondary eclipse, and the full phase curve more generally.

The associated observations and their interpretation are described, with the wider treatment of atmospheres, in Section 11.6. It may avoid confusion to note that while the techniques are generally termed ‘spectroscopy’, and while the goal is to retrieve spectroscopic diagnostics of the planet atmospheres, most observations carried out to date have been based on broad-band photometry.

### 6.24.1 Principles

Transits and secondary eclipses, as part of a planet’s full orbital light curve (shown schematically in Figure 6.26), represent the two occulting configurations which provide particularly important probes of an exoplanet’s atmospheric composition and structure. In both situations, low-resolution spectroscopic or broad-band photometric observations are made in the combined light of the star–planet system (Figure 6.95). Depending on the orbital phase, changes in the integrated flux include effects due to star light blocked by the planet or attenuated by its atmosphere during transit; light scattered, reflected and refracted in or out of transit; and thermal emission intrinsic to the planet or re-radiated by it.

Conditions in the planet’s atmosphere, its chemical composition as well as its structural ( $P - T$ ) profile and energy transport properties, can then be deduced (at least in principle) from the differences in the spectra, or wavelength-dependent flux, as the planet moves in front of, or behind the star.

The measurements are still at the limit of what can be studied from the ground, even for the brightest systems, and they remain challenging even from space.

**Primary transit** When a planet transits in front of its host star, a fraction of the stellar light passes through the narrow annulus of the planet’s atmosphere surrounding its limb (A in Figure 6.95): at wavelengths where the planet atmosphere absorbs the grazing star light more strongly, the transit depth increases.

The wavelength-dependence of the transit depth, and hence the apparent planet radius, effectively provides a *transit spectrum* (or ‘transmission spectrum’). This information can be used to infer the presence (and cross sections) of atoms, molecules, and condensates present in the atmosphere. In the optical, H, C, O, Ca, Na, and K have been detected in the transit spectra, while in the near- and mid-infrared H<sub>2</sub>O and CH<sub>4</sub> are the most prominent species detected.

To a first approximation, the area of the planetary atmosphere intercepted is an annulus of radial extent



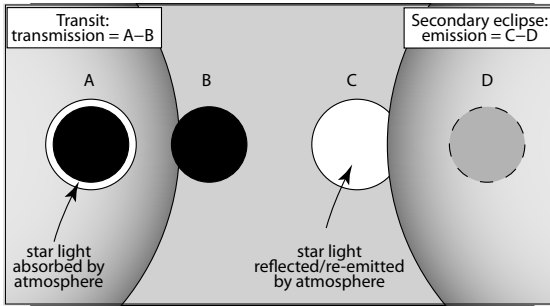


Figure 6.95: Geometry of transmission (left) and emission spectroscopy (right). During the transit, part of the background star light passes through the (annular) atmosphere of the planet. During the secondary eclipse, there is a switching off of the light reflected or emitted from the day-side surface of the planet.

$\approx 5H$  (Seager et al., 2009), where

$$H = \frac{kT}{\mu_m g_p} \quad (6.153)$$

is the atmospheric scale height,  $k$  is Boltzmann's constant,  $T$  the atmospheric temperature,  $\mu_m$  the mean molecular weight, and  $g_p$  is the planet's surface gravity. The fractional contribution of the transmission signal is given by the ratio of the annular to stellar areas

$$\delta \approx 5 \times \frac{2R_p H}{R_\star^2}. \quad (6.154)$$

More detailed models of the transit depth as a function of wavelength require a more complete modeling of the absorption coefficients and mixing ratios for the various absorbers (e.g. Seager & Sasselov, 2000; Brown, 2001b). These considerations lead to a flux decrement, for any given species, of the form (Brown, 2001b, eqn 11)

$$\delta = \frac{2}{\pi R_\star^2} \int_0^{z_{\max}} (R_p + z) \left(1 - e^{-\tau(z,k)}\right) dz \quad (6.155)$$

where  $k = 2\pi/\lambda$  is the wavenumber,  $z$  is the height of the transiting ray above the planet's (reference) surface, and  $\tau$  is the optical depth, itself a function of the species' opacity and wavenumber. Analytic models of general transit theory have been developed along these lines (e.g. Burrows et al., 2001; Lecavelier des Etangs et al., 2008a; Howe & Burrows, 2012).

More detailed treatments take account of refraction in characterising the height of a transiting ray (cf. Brown 2001b, their Figure 4). Other considerations involve the choice of a reference radius, e.g. in the case of an optically-thick atmosphere overlaying a rocky core (Burrows, 2014b).

That transit measurements probe the planet's atmosphere transversely along a chord perpendicular to the impact radius, and integrated over the atmosphere's

annular area, means that the relevant optical depth is much larger than in the radial direction, with the benefit that the transit depth is more sensitive to trace chemical species than spectra acquired at secondary eclipse.

The signature is especially strong for hot, light atmospheres, and low-gravities (cf. Equation 6.154), so that hot Jupiters are particularly effective targets for transit spectroscopy. For a hot Jupiter dominated by a H atmosphere ( $\mu_m = 2$ ),  $\delta \approx 10^{-4}$ . Since the effect scales with  $H$ , and therefore  $\propto \mu_m^{-1}$ , detection of the atmosphere of a (super)-Earth planet by means of CO<sub>2</sub> absorption, for example, is proportionally more of a challenge.

Primary transits probe the exoplanet's atmosphere at the terminator, at both morning and evening sides. In the case of tidally-locked planets, this permits probing substellar to anti-stellar winds. Rich in potential information, the terminator is a complicated region with possible differences in temperature, composition, and scale height between the two limbs, which may result in differences in the ingress and egress transit spectra.

In a related technique, high-resolution ( $R \sim 100000$ ) spectroscopy can isolate the light reflected or emitted from the planet. This has been demonstrated for a small number of planets, both transiting and non-transiting (including  $\tau$  Boo, HD 189733, 51 Peg, and HD 179949), and has the potential to reveal orbital, spin, and wind speeds, as well as atmospheric characterisation (§2.5.4).

Use of transit observations for estimating the planet's mass, through its influence on the atmospheric scale height, is described in Section 6.13.10.

**Secondary eclipse** Typically 180° out of phase with the primary transit (but depending on the orbit eccentricity), observations spanning the secondary eclipse, when the planet passes out of view behind the star, provide a measure of the star light re-emitted (and reflected) by the planet's atmosphere (C in Figure 6.95). This is estimated from the difference between the total light just before or after eclipse (star + planet day-side) and that during the eclipse (star only). The decrement in (thermal) flux that occurs during the eclipse is a measure of the planet's day-side brightness temperature.

The total flux of the star-planet system just outside of the secondary eclipse is given by

$$F_\star + F_p = \Omega_\star B_\star + \Omega_p B_p, \quad (6.156)$$

where  $\Omega$  are the solid angles subtended by the star and planet, and  $B$  are the brightness temperatures. The flux of the system drops by  $\Omega_p B_p$  during eclipse, so that the eclipse depth is (Charbonneau et al., 2005, eqn 1)

$$D_{\text{ecl}} = \frac{\Omega_p B_p}{\Omega_\star B_\star + \Omega_p B_p} \approx \frac{\Omega_p B_p}{\Omega_\star B_\star} = \left(\frac{R_p}{R_\star}\right)^2 \frac{F_p(\lambda)}{F_\star(\lambda)}, \quad (6.157)$$

since  $\Omega_p/\Omega_\star \approx (R_p/R_\star)^2$ . The ratio  $R_p/R_\star$  is accurately constrained by transit observations.



Reflected light (§6.15.1) is ignored in this expression for close-in highly-irradiated planets, and is of order  $(R_p/a)^2$ . As an example, a limit of  $< 8 \times 10^{-5}$  was given for  $\tau$  Boo (Charbonneau et al., 1999).

Observations in the infrared, typically beyond  $1 \mu\text{m}$ , are dominated by the planet's thermal emission, and the method is therefore often referred to as *emission spectroscopy*. Although the thermal emission includes any self-luminosity, close-in planets are emitting mostly reprocessed stellar light (Burrows et al., 2006b, 2008a).

For a 2000 K hot Jupiter, a typical flux decrement during secondary eclipse is  $\sim 200$  ppm at  $2 \mu\text{m}$ , somewhat larger at longer wavelengths (e.g., accessible to Spitzer and JWST), but considerably smaller at optical wavelengths, e.g. at which Kepler observes. For host stars that are bright enough, Kepler's sensitivity provides a direct measure of the planet's disk-averaged day-side flux for the most favourable targets, particularly for the close-in gas giants (the 'hot Jupiters' and 'hot Neptunes').

Secondary eclipse spectroscopy exploits the fact that the planet's brightness temperature generally varies with wavelength, i.e. the spectrum deviates from that of a blackbody. This is primarily because of the atmosphere's wavelength-dependent opacity and vertical temperature profile (e.g. Deming et al., 2005b; Seager et al., 2005a; Barman et al., 2005; Burrows et al., 2007b, 2008a; Fortney et al., 2008a; Knutson et al., 2008; Désert et al., 2009).

**Atmospheric modeling** The star and planet spectra are then modeled by (for example) radiative-transfer calculations (or the derivative 'spectral retrieval' or 'atmospheric retrieval' approach), accounting for scattering, and ionic, atomic and molecular opacities. The goal is to recover information on the atmospheric composition through the observed spectral lines, along with information on its temperature and thermal structure.

Qualitatively, absorption lines broadly indicate decreasing temperature with height, while emission lines signify the converse. If a stratosphere is present, molecular signatures can appear either in emission or in absorption, depending on their formation region above or below the tropopause. Spectral interpretation therefore requires the simultaneous retrieval of the atmosphere's temperature profile. Stellar irradiation and zonal atmospheric winds break any spherical symmetry.

If different wavelengths probe the same atmospheric layer (e.g., a cloud deck) then the planet will appear to have a blackbody spectrum. In the absence of clouds, a planet may still have a blackbody spectrum if the atmospheric layers probed are isothermal.

In summary, phenomena that influence secondary eclipse spectra, and which have been widely discussed in the literature, include the compositions and elemental abundances of the atmospheres (including the presence of hazes and clouds, the planet's albedo, and pos-

sible disequilibrium chemistry); its temperature profile (including thermal inversions); and the day/night temperature contrasts (including phase shifts due to zonal winds). These are discussed further in Section 11.6.

**Complementarity** Transit and eclipse spectra are somewhat complementary. In contrast with transit observations, the day-side of the planet is visible around secondary eclipse (C in Figure 6.95). Transit spectra are more directly sensitive to molecular composition and atmospheric scale height than to temperature profile, while secondary eclipse spectra yield both thermal and compositional information. As noted above, during the primary transit, stellar light traverses the planet's atmosphere transversely, rather than radially, and the larger geometrical column can reveal trace species less evident in the emission spectrum.

**Phase curves** Outside of the transit and eclipse phases, the flux of the star–planet system over the full orbital period gives the planet emission at different phase angles (cf. Figure 6.26). The resulting *phase curve* can be used as a further diagnostic of temperature profiles, day-to-night energy transport, winds, and more generally, the dynamical evolution of the atmosphere, or 'weather'. Again, such observations are typically only accessible from space, beyond Earth's atmosphere, and further benefit from access to the near- and mid-infrared.

The first complete orbit light curve, for CoRoT–1, as observed by the CoRoT satellite itself (Snellen et al., 2009a), illustrates the type of orbit light curve that has since been obtained for a small number of other transiting systems. The satellite data over 55 d, phase folded at the orbital period (Figure 6.96), show the transits, followed by an increasing flux as the day-side hemisphere rotates into view, followed by the secondary eclipse by the star, before the planet rotates out of view again.

Results from these types of observation and analyses are discussed further in Section 11.6.3.

**Non-transiting systems** Planetary thermal emission spectra can also be probed for non-transiting planets. From multi-epoch Keck–NIRSPEC near-infrared observations of the non-transiting planet HD 88133 b ( $P = 3.4$  d), Piskorz et al. (2016) isolated the planet's atmospheric emission (deriving an opacity structure dominated by  $\text{H}_2\text{O}$ ), measured a radial projection of the Keplerian orbital velocity of  $40 \pm 15 \text{ km s}^{-1}$ , and a nearly face-on orbital inclination of  $15 \pm 5^\circ$ , corresponding to a true mass of  $M_p = 1.02^{+0.61}_{-0.28} M_J$ .

### 6.24.2 Equilibrium temperature and albedo

**Planet equilibrium temperature** Secondary eclipse diagnostics are derived from the object's spectral features in principle, but generally from its deviation from a blackbody spectrum based on medium-band photometry in practice.

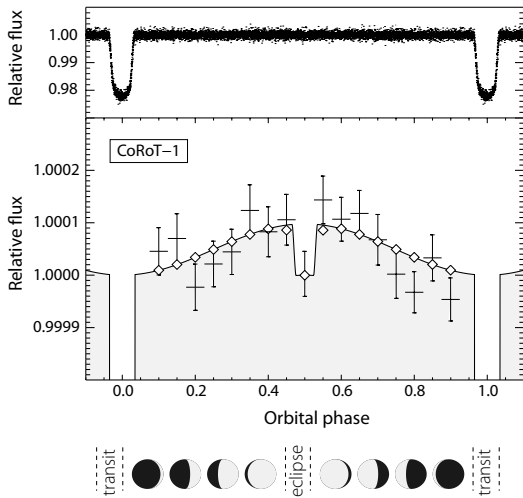


Figure 6.96: CoRoT-1 b observed over 55 days (36 orbits), and phase-folded at the orbital period  $P = 1.5089557$  d. In the centre panel the data are binned in phase intervals of 0.05. The data are consistent with the day-side hemisphere rotating into view, being eclipsed by the star, and rotating out of view again (bottom schematic). The solid curve is a model assuming uniform (but distinct) brightness for the day and night hemispheres. From Snellen et al. (2009a, Figure 1), by permission from Nature/Springer/Macmillan Ltd, ©2009.

The *equilibrium temperature* of an irradiated planet,  $T_{\text{eq}}$ , is defined as the surface blackbody temperature for which the incident stellar flux is balanced by the energy absorbed and re-radiated by the planet or its atmosphere. By appeal to the Stefan–Boltzmann law, and ignoring other possible heat sources (e.g. tidal deformation, radiogenic decay, and greenhouse effect), it can be written (e.g. Charbonneau et al., 2005, eqn 2)

$$T_{\text{eq}} = T_{\star} \left( \frac{R_{\star}}{2a} \right)^{1/2} [f(1 - A_{\text{B}})]^{1/4}, \quad (6.158)$$

where  $T_{\star}$  is the stellar effective temperature,  $a$  is the planet’s semi-major axis, and  $A_{\text{B}}$  is the Bond albedo (see below). An upper limit on  $T_{\text{eq}}$  is given by setting  $A_{\text{B}} = 0$ . The heat redistribution factor,  $f$ , describes the effectiveness of atmospheric circulation and heat transfer, and is frequently defined (numerically, via Equation 6.158) differently by different authors. In this definition (e.g. Charbonneau et al., 2005; Méndez & Rivera-Valentín, 2017),  $f = 1$  if the planetary emission is isotropic (e.g. fast rotators), and  $f = 2$  if only the planet day-side reradiates the energy absorbed (e.g. tidally-locked planets without oceans or atmospheres). If  $R_{\star}$  is unknown, it can be estimated from the stellar surface gravity (Kane & Gelino, 2011a, their eqn 2).

Orbital eccentricity introduces a time dependency to the value of  $T_{\text{eq}}$ , although the form of Equation 6.158 shows that  $T_{\text{eq}}$  is more sensitive to the (typically well-determined) orbital properties than on the atmospheric

dynamics, which are generally unknown. Méndez & Rivera-Valentín (2017) showed that the average equilibrium temperature, for a planet with constant albedo, slowly decreases with increasing  $e$ , converging to a value  $\sim 90\%$  that of a circular orbit (their eqn 20)

$$\langle T_{\text{eq}} \rangle = T_0 \left[ \frac{f(1 - A_{\text{B}})L_{\star}}{\epsilon a^2} \right]^{1/4} \frac{2\sqrt{1+e}}{\pi} E \left( \sqrt{\frac{2e}{1+e}} \right), \quad (6.159)$$

where  $T_0 = 278.5$  K,  $L_{\star}$  is the star luminosity (solar units),  $a$  is the semi-major axis (au),  $\epsilon$  is the emissivity, and  $E$  is the complete elliptic integral of the second kind. The effect on habitability is discussed in Section 11.7.4. In practice, the actual equilibrium and surface temperatures will also depend on orbital variations of the albedo and greenhouse effects.

The effective temperatures of isolated self-luminous giant planets of Gyr ages range from  $\sim 50$ – $500$  K, which results in a very small contribution to the emergent flux if the planet is strongly irradiated. The planet’s contribution is significant only when the stellar irradiation flux is small, and thus only for wide-separation planets.

**Bond albedo** The *Bond albedo*,  $A_{\text{B}}$ , is the fraction of energy reemitted relative to the amount received, integrated over all wavelengths. It can be estimated by determining the planet’s brightness temperature from multi-wavelength observations, and using this estimate in place of  $T_{\text{eq}}$  in Equation 6.158, along with a value of  $f$  inferred from orbital brightness variations. For practical examples, see e.g. Charbonneau et al. (2005, Section 4.1) or Angerhausen et al. (2015a, Section 2.4).

Compared with Jupiter and the other solar system gas giants, which have (geometric and Bond) albedos in the range 0.3–0.5, measurements with CoRoT and Kepler in the optical, and Spitzer in the infrared, have shown that the albedo of most hot Jupiters is typically  $\leq 10\%$  (e.g. Knutson et al., 2009c; Cowan & Agol, 2011b), comparable to that of the Moon. High-precision optical photometry of HD 209458 b with MOST gave a geometric albedo of only 4% (Rowe et al., 2008), while other observations are consistent with zero (e.g. WASP-18, Nymeyer et al., 2011). The implication is that hot Jupiters are generally dark, consistent with early theoretical models of giant planet atmospheres which predict the removal of reflective cloud layers in these extreme stellar flux regimes (e.g. Sudarsky et al., 2003).

Exceptions to these low albedos include Kepler-7 b, with an almost Jupiter-like albedo of 0.32. This ‘excess’ reflection suggests the presence of a cloud or haze layer in its atmosphere (Demory et al., 2011b).

Beyond the hot-Jupiter regime, models (e.g. Marley et al., 1999; Sudarsky et al., 2005) indicate that the albedo drops significantly between 1.0–1.2  $\mu\text{m}$ , relatively independent of the star–planet separation.

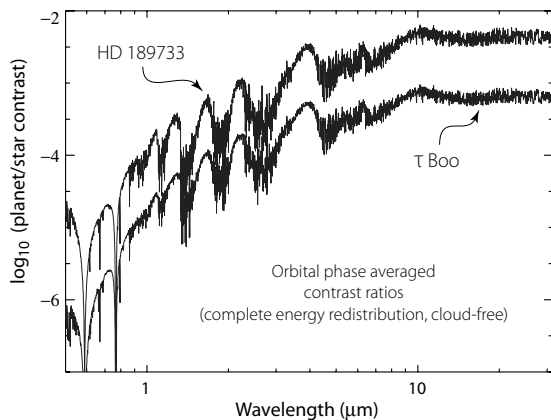


Figure 6.97: Theoretical planet–star contrast versus wavelength for the gas giants HD 189733 and  $\tau$  Boo. HD 209458, TrES–1, and 51 Peg lie between the two. Models assume complete energy redistribution, and ignore cloud effects. From Burrows et al. (2006b, Figure 1), by permission of IOP Publishing/AAS.

### 6.24.3 Observations

While ground-based observations have contributed to transit and eclipse spectroscopy (cf. Tables 11.5–11.6), space observations have dominated, mainly because of access to wavelengths blocked by Earth’s atmosphere.

HST (§6.10.2) has provided access to the ultraviolet (with STIS) and to the near-infrared (with NICMOS).

Spitzer (§6.10.5), using IRS, MIPS, and IRAC (the latter in both its ‘cold’ and long-wavelength restricted ‘warm’ mission phases), has given access to the mid-infrared and beyond, where limb darkening is less significant, where the planet–star contrast is improved (from  $10^{-5}$ – $10^{-6}$  in the optical to  $10^{-3}$ – $10^{-4}$  in the infrared; cf. Figure 6.97), and where a number of strong molecular absorption bands, including  $\text{H}_2\text{O}$ , CO,  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{NH}_3$  are present. It has provided near- and mid-infrared photometry for 30–40 (mostly) hot transiting giant planets around nearby bright stars (Table 11.8).

For the future, substantial advances are expected with the launch of JWST (§11.6.4).

**Transmission spectroscopy of Earth** An analogous instrument for probing Earth’s atmosphere was the spectrometer SCIAMACHY (SCanning Imaging Absorption SpectroMeter for Atmospheric CHartography), one of ten instruments on ESA’s environmental satellite, ENVISAT (operational 2002–12). It was designed to measure transmitted, reflected and scattered sunlight in the ultraviolet to near-infrared ( $0.24$ – $2.38 \mu\text{m}$ ) at  $R \sim 0.2$ – $1.5$  nm, to improve knowledge of the chemistry and physics of Earth’s troposphere, stratosphere and mesosphere (e.g. Bovensmann et al., 1999; Frankenberg et al., 2008). Instruments focusing on  $\text{O}_3$  monitoring, GOME, were carried on the three MetOp polar orbiting meteorological satellites (e.g. Burrows et al., 1999).

## 6.25 Range of properties of transiting planets

A summary of some of the extreme properties of transiting systems is given in Table 1.6.

**Host stars** Most transiting planets orbit stars with masses close to  $1M_\odot$ , with extremes ranging from  $0.08M_\odot$  for TRAPPIST–1 and  $0.13M_\odot$  for Kepler–42, to  $2.1M_\odot$  for Kepler–340 and some 20 others exceeding  $1.5M_\odot$ . Stars of spectral type later than K are too faint to be found in large numbers by wide-field transit surveys, while those earlier than F have rotationally broadened spectral lines and inherent stellar noise that may restrict radial velocity follow-up.

In distance, transiting systems range from the nearest, GJ 1132 and TRAPPIST–1 at around 12 pc, out to beyond 2–3 kpc for the most distant Kepler hosts.

Host star magnitudes range from the brightest at around  $V \sim 8$  mag for KELT–11, WASP–33, and Kepler–21, to the faintest Kepler transiting host stars at around  $V \sim 17$  for Kepler–445. Slightly fainter optical magnitudes pertain for the systems POTS–1, TRAPPIST–1, SWEEPS–4, and SWEEPS–11.

The highest planet multiplicities reach eight in the case of Kepler–90 (KOI–351), seven for TRAPPIST–1, six for Kepler–11, Kepler–20 and Kepler–80, and with a number containing five known planets.

**Planets** Properties of transiting planets vary widely. Inferred masses range from  $0.07M_\oplus$  (Kepler–138 b),  $0.20M_\oplus$  (Kepler–453 b), and  $0.4$ – $0.6M_\oplus$  (TRAPPIST–1 d and e), to  $\sim 15$ – $30M_J$  for the brown-dwarf borderline Kepler–47 c, KELT–1 b, and CoRoT–3 b.

Some are significantly larger for their mass than expected from gas giant models (including HD 209458, WASP–2, and TrES–4), while others are significantly smaller (including HD 149026 and HAT–P–3). These anomalous radii are discussed further in Section 6.28.4.

Densities range from as low as  $0.02$ – $0.08 \text{ Mg m}^{-3}$  (K2–97 b, Kepler–51 bcd, HAT–P–67 b, and WASP–17 b), through the  $0.6$ – $1.3 \text{ Mg m}^{-3}$  more typical of the solar system gas giants, to  $\sim 5.5$ – $7.5 \text{ Mg m}^{-3}$  indicating rocky planets with densities comparable to the Earth (e.g. CoRoT–7), and extending to the  $25 \text{ Mg m}^{-3}$  of the brown dwarfs CoRoT–3 and KELT–1. Notably high densities have also been inferred for a number of low-mass planets, including Kepler–131 c, Kepler–406 c, and K2–38 b, although all with rather large errors.

Orbital periods are below 0.5 d for three planets: Kepler–78 b, K2–22 b and Kepler–42 c. Of nearly 3000 transiting planets known, 2.5% are below 1 d, 51% are below 10 d, 95% are below 100 d, and only 20 (0.7%) are above 1 yr. Of those discovered from transit measurements, the longest periods tend to be in systems with known shorter-period transiting planets (which constrain the geometries). Exceeding 1000 d are Kepler–539 c, Kepler–167 e, and Kepler–1647 b, with the longest

known, WASP-53 c, at 2840 d.

Stellar irradiation and tidal effects for the close-in planets are substantial. As one example, WASP-12 b has an equilibrium temperature of  $\approx 2510$  K, and the stellar disk would subtend an angle of  $35^\circ$  from its surface. Its inferred tidal bulge implies a predicted apsidal precession of  $19.9^\circ \text{yr}^{-1}$  (Ragozzine & Wolf, 2009).

Some planets follow highly eccentric orbits. Of those discovered by transit measurements, three have  $e > 0.6$ , specifically WASP-53 c ( $e = 0.84$ ), Kepler-419 b ( $e = 0.83$ ), and Kepler-420 b ( $e = 0.77$ ). Even larger is the transiting planet discovered through radial velocity measurements, HD 80606 b, with  $e \approx 0.93$ .

Orbit inclinations are generally close to the  $90^\circ$  expected for transiting systems, with a few close-in planets as small as  $i \approx 78 - 80^\circ$  (KELT-14 b and WASP-19 b), and as low as  $69.7 \pm 0.7$  for Kepler-91 b.

Many have orbits highly inclined to the stellar rotation axis (§6.18), with a number (including HAT-P-7 and WASP-17) being on retrograde orbits.

Angular star-planet separations as seen from Earth are small, and typically  $\lesssim 2$  mas. Larger angles are subtended by a few systems, e.g. 3 mas for the nearby GJ 436 b, and 8 mas for the long-period HD 80606.

## 6.26 Kepler distributions and occurrence rates

The scientific results from Kepler are especially broad, interlinked with other scientific aspects (both within and beyond the mission and transit photometry), and in many cases still developing rapidly. A number of reviews have covered various aspects of these, including a broad review of the overall advances in exoplanet science (Lissauer et al., 2014a), and the overall occurrence and architecture of exoplanetary systems (Winn & Fabrycky, 2015; Hatzes, 2016a).

### 6.26.1 Size and period distributions

As of the end of 2017, the NASA Exoplanet Archive of confirmed planet lists more than 2700 transiting planets, of which  $\sim 2300$  are from Kepler (excluding those from the K2 mission extension). The distribution of  $R_p$  versus  $P$  is shown in Figure 6.98.

The Kepler results provide a wealth of insights into the structure and properties of planetary systems: it is large enough to map out the distribution of planets in multiple parameters (such as orbital period, radius, multiplicity, and properties of the host star). Importantly, it has rather well-defined selection criteria, somewhat in contrast to radial velocity catalogues, which come from many different surveys and which usually do not include null results. Most of the Kepler parameter space,  $R_p \sim 1 - 3R_\oplus$  and  $P \lesssim 1$  yr, is not easily accessible by other techniques.

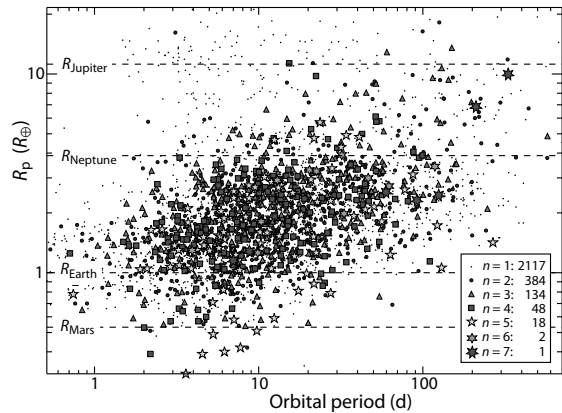


Figure 6.98:  $R_p$  versus  $P$  for planet candidates from the first 3 years of Kepler data. Symbols show the number of candidates in the system. Numbers in the legend are the total number of systems of a given multiplicity. Smaller periods are over-represented because geometric factors and frequent transits make them easier to detect. The upward slope in the lower envelope arises from the difficulty in detecting small planets (for which transits are shallow) with long periods (for which fewer transits are observed). The apparent absence of giant planets in multi-planet systems has been quantitatively confirmed (e.g. Latham et al., 2011). From Lissauer et al. (2014a, Figure 1), by permission from Nature/Springer/Macmillan Ltd, ©2014.

Most have orbital periods shorter than a few months, and have  $R_p$  intermediate between those of Earth and Neptune ( $1 - 3.8R_\oplus$ ); a size range missing from the solar system. These planets have a wide range of densities (Batalha et al., 2011; Lissauer et al., 2011a; Doyle et al., 2011; Carter et al., 2012; Jontof-Hutter et al., 2014; Marcy et al., 2014), probably because they have atmospheres with a wide range of properties. Theoretical models of their interiors imply that all of the planets in this class are ‘gas-poor’, with less than half (in most cases far less) of their mass consisting of H and He (and in contrast with almost all known giant exoplanets with  $R_p > 9R_\oplus$ ).

Almost half of Kepler’s planet candidates are in systems in which multiple transiting planets have been found (§6.30). The abundance of such systems implies that flat systems containing multiple planets on closely spaced orbits are quite common (§6.30.5).

**Size distribution** Borucki et al. (2011b) presented the size distribution from the first 4 months of Kepler data according to five classes. Updated to the end of 2017, the distribution of all transiting planet radii, dominated by Kepler results, is (as in Table 1.3):

- 373 are  $< 1.25R_\oplus$ , i.e. approximately Earth-size,
- 766 are  $1.25 - 2R_\oplus$  (super-Earths),
- 1187 are  $2 - 6R_\oplus$  (Neptune-size),
- 361 are  $6 - 15R_\oplus$  (Jupiter-sized), and
- 121 in the range  $15 - 22R_\oplus$  (i.e. up to  $2R_J$ ).

### 6.26.2 Eccentricities

The eccentricities of many Kepler planets, while important for studies of formation and evolution, are unknown, since detailed orbits from radial velocity measurements are generally precluded by the faintness of the host stars. Other estimates of orbital eccentricities have been formulated.

One possibility for determining  $e$ , if the secondary eclipse can be detected (and therefore mainly of relevance for hot close-in planets), is from the comparative timing of the primary and secondary eclipses (§6.13.6). Again of relevance typically only for hot Jupiters,  $e$  can occasionally be determined photometrically from the photo-eccentric effect (§6.13.11; Dawson & Johnson, 2012; Dawson et al., 2012, 2015b).

Eccentricities and planet mass ratios can also be inferred from some multi-transiting systems showing transit time variations (§6.20). Although  $e$  and  $M_p$  are typically correlated when derived in this way,  $e$  can sometimes be inferred from statistical arguments (Lithwick et al., 2012; Wu & Lithwick, 2013a), or from the effect of synodic ‘chopping’ (§6.20.3; Deck & Agol, 2015), and both low and high eccentricities have been found (Hadden & Lithwick, 2014). However, transit time variations are only detected in a subset of multiple transiting systems, typically near resonances, and it is not clear whether these have undergone the same evolution.

In the absence of individual eccentricities, some constraints on their distribution can be inferred from the distribution of transit durations. The varying velocity for planets on eccentric orbits (from Kepler’s second law) results in a different transit duration relative to a circular orbit: transits can be of longer or shorter duration depending on the orbit orientation.

Transit durations for circular orbits are governed by the mean stellar density (Seager & Mallén-Ornelas, 2003, see also §6.13.5 and §6.13.11). Therefore if the stellar density is known independently, then a comparison of the two constrains  $e$  independently of  $M_p$  (Ford et al., 2008a; Tingley et al., 2011a). This was attempted by Moorhead et al. (2011), although they were limited by uncertainties and possible systematics in the host star densities. Eccentricities for a large and homogeneous sample of 698 Kepler planets were estimated in this way (nearly half in single-planet systems, the remainder in multi-planet systems), based on stellar densities determined from spectroscopy with the LAMOST telescope (Xie et al., 2016). They found that, on average, Kepler single planets are on eccentric orbits with  $\langle e \rangle \sim 0.3$ , whereas multiples are on nearly circular ( $\langle e \rangle = 0.04^{+0.03}_{-0.04}$ ) and coplanar ( $\langle i \rangle = 1.4^{+0.8}_{-1.1}$  deg) orbits similar to those of the solar system planets (see also §2.10.4).

Van Eylen & Albrecht (2015) estimated eccentricities, using Kepler transit photometry, for 28 bright stars with precise asteroseismic densities. These stars host

74 planets with an average radius of  $2.6R_\oplus$ . They found that the eccentricity in these multi-planet systems is low, and can be described by a Rayleigh distribution with  $\sigma = 0.049 \pm 0.013$ . This is in agreement with solar system eccentricities, but in contrast to the eccentricity distributions previously derived for exoplanets from radial velocity studies.

A related method uses characteristics of the transit profile, short ingress/egress/total transit durations, part of the ‘photo-eccentric’ light curve signature of a planet’s eccentricity (see §6.13.11).

### 6.26.3 Occurrence rates

Kepler has confirmed that planets are common, with the number of planets in the extended solar neighbourhood of the Galaxy being comparable to or larger than the number of stars (Dressing & Charbonneau, 2013).

The probability distribution can be expressed as  $f(R_p, P) d \ln R_p d \ln P$  that a member of a specified stellar class possesses a planet in the element  $d \ln R_p d \ln P$  (Tabachnik & Tremaine, 2002; Youdin, 2011b; Howard et al., 2012b; Dong & Zhu, 2013; Lissauer et al., 2014a). The integral of this distribution over a range in planetary radius and orbital period is the *average number of planets per star* (which is not the same as the fraction of stars with planets, which is smaller). Kepler has determined this distribution for solar-type stars with reasonable accuracy for  $R_p \geq 1R_\oplus$  in the range  $P \leq 50$  d, and for  $R_p \geq 2R_\oplus$  in the range  $P \leq 150$  d.

**Estimating occurrence rates** Estimates of occurrence rate must account for the completeness, reliability, and threshold criteria of the Kepler catalogue (Jenkins et al., 2010c; Tenenbaum et al., 2012), as well as random and systematic errors and biases in the host star properties (Gaidos & Mann, 2013). For candidates with small transit depths or few transits, robust estimates require calibration by injecting and recovering simulated planetary signals (Petigura & Marcy, 2012; Petigura et al., 2013b,a; Christiansen et al., 2013, 2015, 2016). The false-positive frequency distribution must also be modeled (Fressin et al., 2013). Revisions of host star properties can substantially alter the radius distribution (Dressing & Charbonneau, 2013).

**Resulting distributions** Batalha (2014) summarised occurrence rates as follows: the number of planets per unit log period is nearly flat for  $R_p \leq 4R_\oplus$  and  $P > 10$  d. It rises by a factor 2–5 between  $P = 10 - 100$  d for larger planetary radii, but drops sharply below  $P = 10$  d for  $R_p \leq 4R_\oplus$ , and below  $P = 2 - 3$  d for giant planets.

The occurrence rate of giant planets on small orbits is a factor of three lower than in radial velocity surveys (Howard et al., 2012b; Wright et al., 2012; Fressin et al., 2013). This may be because a significant fraction of giant planets are injected into small orbits through

planet–planet gravitational interactions, and the relatively metal-poor Kepler stars host fewer and/or less massive planets, which are less likely to interact strongly (Dawson & Murray-Clay, 2013).

At all periods, the number per log  $R_p$  grows with decreasing  $R_p$ , at least down to  $2R_\oplus$ . Below  $2R_\oplus$ , the distribution flattens at orbital periods out to 50 d and probably to 100 d (Dong & Zhu, 2013; Petigura et al., 2013b).

The average number of planets per star with  $P < 50$  d is  $\sim 0.2$  for  $1R_\oplus < R_p < 2R_\oplus$  and  $\sim 0.4$  for  $R_p > 1R_\oplus$  (Dong & Zhu, 2013; Petigura et al., 2013a,b). Burke et al. (2015) estimated an occurrence rate of 0.77 planets per star for GK dwarfs, for  $0.75R_\oplus < R_p < 2.5R_\oplus$  and  $50 < P < 300$  d. Fressin et al. (2013) estimated that  $16.5 \pm 3.6\%$  of main sequence FGK stars have at least one planet between  $0.8 - 1.25R_\oplus$  with orbital periods up to 85 d.

For stars cooler and less massive than the Sun, the average number is still higher (Dressing & Charbonneau, 2013):  $0.49^{+0.07}_{-0.05}$  for  $1R_\oplus < R_p < 2R_\oplus$  and  $0.69^{+0.08}_{-0.06}$  for  $R_p > 1R_\oplus$  with  $P < 50$  d.

**Metallicity dependence** Radial velocity surveys have established that giant planets are more common around stars of higher metallicity (§2.9.4). The Kepler data suggest that no comparable trend exists for small planets (Buchhave et al., 2012).

**Earth-like planets** Of particular interest is  $\eta_\oplus$ , the average number of Earth-like planets per star. The definition of ‘Earth-like’ is, however, rather ambiguous (as detailed in Section 11.7.4).

An assessment made from the various Kepler results by Lissauer et al. (2014a) started with the definition of ‘Earth-size’ as  $0.5 - 1.4R_\oplus$  (e.g. Kopparapu, 2013). For solar-type stars he adopted  $\eta_\oplus = f(1R_\oplus, 1 \text{ yr})$ ; for other stars, the 1-yr period can be replaced with that corresponding to the same incident stellar flux.

Lissauer et al. (2014a) gave  $\eta_\oplus = 0.09$ , by adopting power-law fits of the form  $f(R_p, P) \propto P^\beta$  to the distribution of planets in the 16-month Kepler catalogue (Dong & Zhu, 2013);  $\eta_\oplus = 0.12 \pm 0.04$  from an independent analysis of Kepler light curves (Petigura et al., 2013b), after renormalising by a factor 2.1 to account for their definition of  $\eta_\oplus$ ; and a smaller value  $\eta_\oplus = 0.02^{+0.02}_{-0.01}$  using the same catalogue but a more general form for the distributions in  $P$  and  $R_p$  (Foreman-Mackey et al., 2014).

In other Kepler studies, Traub (2012) predicted that one third of FGK stars have at least one habitable zone planet. Petigura et al. (2013a) estimated that 22% of Sun-like stars might host a habitable zone rocky planet, that 11% of Sun-like stars harbour an Earth-size planet receiving between one and four times the stellar intensity as Earth, that the occurrence of Earth-size planets is constant with increasing orbital period within equal intervals of log  $P$  up to 200 d, and that  $5.7^{+1.7}_{-2.2}\%$  of Sun-like stars harbour an Earth-size planet with  $P \sim 200 -$

400 d. Gaidos (2013) gave  $\eta_\oplus = 0.46^{+0.18}_{-0.15}$  for the fraction around Kepler dwarf stars. Burke et al. (2015) gave  $\eta_\oplus \sim 0.1$  for a sample of GK hosts.

While there is no clear consensus, Earth-like planets do appear to be common.

**M dwarfs** M dwarfs are of particular interest since they may be the most abundant planet hosts in the Galaxy, and at the same time offer good prospects for characterising terrestrial planets in their habitable zones (§2.8.4).

In addition to the standard pipeline processing, Swift et al. (2015b) performed an independent uniform analysis for M stars, recovering all but two of the signals previously reported. Using the cool dwarf photometric cuts of Mann et al. (2012), and additional vetting using near-infrared medium-resolution spectroscopy (Muirhead et al., 2012b, 2014), their final Kepler M dwarf sample contains 163 planets around 104 cool stars. The total number of single transit systems is 74; there are 12 double systems, 10 triple systems, 5 quadruple systems, and 3 quintuple systems. A total of 54.6% of planets are found in multi-transit systems, and 12.4% of these show significant transit timing variations. In contrast, only one single transit system out of 74 shows a significant TTV signal. Examining their mutual inclinations, Ballard & Johnson (2016) found that the ‘Kepler dichotomy’ (§6.30.6) holds for both M dwarfs as well as solar-type stars, albeit perhaps with different fractional populations (Moriarty & Ballard, 2016).

Various estimates of occurrence frequencies of planets around M dwarfs have been made.

Gaidos et al. (2016) determined that Kepler M dwarfs host an average of  $2.2 \pm 0.3$  planets with  $R_p = 1 - 4R_\oplus$  and  $P = 1.5 - 180$  d. The radius distribution peaks at  $1.2R_\oplus$  and is essentially zero at  $4R_\oplus$ .

Muirhead et al. (2015) estimated that  $21 \pm 6\%$  of mid-M dwarfs host compact ( $P < 10$  d) multiples for a wide range of metallicities, the inferred planet masses suggesting highly efficient accretion of protoplanetary disk metals by mid-M dwarf protoplanets.

Within the habitable zone of M dwarfs, Dressing & Charbonneau (2013) estimated a frequency of  $0.15^{+0.13}_{-0.06}$  per star for terrestrial-size planets ( $0.5 - 1.4R_\oplus$ ) using the habitable zone limits of Kasting et al. (1993), although invalid  $T_{\text{eff}} < 3700$  K. Kopparapu (2013) revised the result using the revised habitable zone limits from Kopparapu et al. (2013) for stars with  $2600 < T_{\text{eff}} < 7200$  K, which includes the cool M stars in the Kepler target list. The new boundaries result in a higher terrestrial planet frequency of  $0.48^{+0.12}_{-0.24}$  and  $0.53^{+0.08}_{-0.17}$  planets per M dwarf for conservative and optimistic limits of the habitable zone boundaries, respectively. Increasing the range of Earth-size planets to  $0.5 - 2R_\oplus$ , the frequency increases to  $0.51^{+0.10}_{-0.20}$  and  $0.61^{+0.07}_{-0.15}$  per star respectively.

These high-occurrence rates are in reasonable agreement with estimates from M dwarf radial velocity

surveys, of  $0.41_{-0.13}^{+0.54}$  (Bonfils et al., 2013a). They would increase by a further factor of  $\sim 1.6$  if extended over the interval used to define  $\eta_{\oplus}$  by Lissauer et al. (2014a).

**Venus-like planets** Within the solar system, there is a clear distinction between Venus and Earth in terms of their atmospheric evolution, presumably attributable to the factor  $\sim 2$  difference in incident solar flux. However, with  $R_{\text{Venus}} \sim 0.95R_{\oplus}$ , it is impossible to distinguish between two such planets based only on size.

Kane et al. (2014b) examined planetary insolation, atmospheric erosion, and runaway greenhouse limits for planets similar to Venus. They defined a *Venus zone* in which the planet is more likely to be a Venus analogue rather than an Earth analogue, and identified 43 potential Venus analogues in the Kepler catalogue.

These numbers yield occurrence rates of  $\eta_{\text{Venus}} = 0.32_{-0.07}^{+0.05}$  for M dwarfs, and  $0.45_{-0.09}^{+0.06}$  for GK dwarfs.

**Long-period transiting planets** Long-period transiting planets are rarely found, due to a combination of their infrequent transits, and their smaller geometric transit probability. This intrinsic bias of transit surveys in favour of short-period planets (Beatty & Gaudi, 2008) is evident in the paucity of known long-period planets, even from the long-staring Kepler mission, and even with specific efforts to identify long-period candidates from single transit events (§6.12.3).

Of the Kepler planets, 27 have  $P > 300$  d, of which 9 (out to  $P \sim 1000 - 3000$  d) are *non-transiting companions* to transiting discoveries which were subsequently discovered through radial velocity measurements, while one (Kepler-419 c) is a non-transiting companion inferred from transit timing variations.

Four transiting Kepler planets with  $P > 700$  d are known. Kepler-421 b is a  $P = 704.2$  d Uranus size planet in a near-circular orbit near the snow-line, transiting a G9/K0 dwarf (Batalha et al., 2013; Burke et al., 2014; Kipping et al., 2014c). Kepler-539 c ( $P > 1000$  d) and Kepler-167 e ( $P = 1071$  d) are in multi-planet transiting systems.

The most extreme, Kepler-1647 b with  $P = 1108$  d, is a single  $1.1R_{\text{J}}$  planet in a circumbinary orbit ( $P_{\text{bin}} = 11$  d,  $e_{\text{bin}} = 0.16$ ). The planet produced three transits in the light curve of Kepler-1647 (one of them during an eclipse, creating a syzygy; §6.14.16) and measurably perturbed the times of the stellar eclipses, providing a mass estimate,  $M_{\text{p}} = 1.52 \pm 0.65M_{\text{J}}$ . Despite an orbital period three times longer than Earth's, Kepler-1647 b is in the habitable zone of the binary star throughout its orbit.

Kepler-167 e, with  $R_{\text{p}} = 0.9R_{\text{J}}$ ,  $e = 0.06$ , and  $P = 2.9$  yr, has been considered as a transiting *Jupiter analogue* (Kipping et al., 2016).

Foreman-Mackey et al. (2016) estimated an average occurrence rate for solar-type stars, for  $R_{\text{p}} < R_{\text{J}}$  and  $P = 2 - 25$  yr, to be  $2.0 \pm 0.7$  planets per star.

As a result, Kepler provides important but still limited constraints on the population of Jupiter-like planets

or Jupiter-like systems, a subject that should be transformed by the Gaia mission results.

**Habitable zone planets and frequency** Planets within the habitable zone are considered in Section 11.7.4.

## 6.27 Mass, radius, and composition

There is an extensive literature on the mass–radius relation for transiting planets, and on the resulting constraints on planet formation (Chapter 10) and on their interior composition and atmospheres (Chapter 11).

The mass–density relation for the subset of CoRoT planets is discussed separately in Section 6.5 (see also Figure 6.10). Other aspects of the mass–radius relation in the context of interior and atmosphere models are covered in Section 11.5.

**Overall features** An early mass–radius diagram for transiting planets, constructed at the very start of the Kepler mission and showing the observed relationship for various HAT, WASP, CoRoT, and other planets, is shown in Figure 6.99. It shows a clustering in the range  $0.5 - 1M_{\text{J}}$  and  $0.9 - 1.5R_{\text{J}}$ , with few objects with densities below  $\sim 0.25\rho_{\text{J}}$ , and few above  $\sim 10\rho_{\text{J}}$ . For these brighter host stars, planet masses could be derived from follow-up radial velocity observations, while this option is not available for the majority of the fainter Kepler host stars.

Figure 6.100 shows another early representation of the mass–radius relation for transiting planets in a diagram which includes stars and substellar objects covering more than three orders of magnitude in mass, extending from the stellar and substellar regime down to the hot gaseous planets. The two lines are theoretical models of solar composition, and for two isochronal ages. That the broad observational features are reasonably replicated by theory suggests that the overall description of their internal structure, composition, and heat content was already tolerably well understood.

The detailed structure of this diagram is discussed by Chabrier et al. (2009). The general behaviour is reflected in the polytropic mass–radius relation  $R \propto M^{(1-n)/(3-n)}$  (Burrows & Liebert, 1993; Chabrier & Baraffe, 2000). For low-mass stars with large radiative cores  $n \approx 3$ , decreasing to  $n = 3/2$  below  $0.4M_{\odot}$  when the star becomes fully convective. From the bottom of the main sequence, below the hydrogen-burning minimum mass, brown dwarfs are supported primarily by electron degeneracy. As mass decreases the increasing electrostatic contribution (Coulomb pressure) leads to a decreasing density, and a decrease in  $n$  to a value  $n = 1$  at a few  $M_{\text{J}}$ . In terms of an equation of state relating pressure and density,  $P \propto \rho^{\gamma}$  with  $\gamma = 1 + 1/n$ , the decreasing polytropic index from stars to planets broadly corresponds to progressively less compressible interiors.

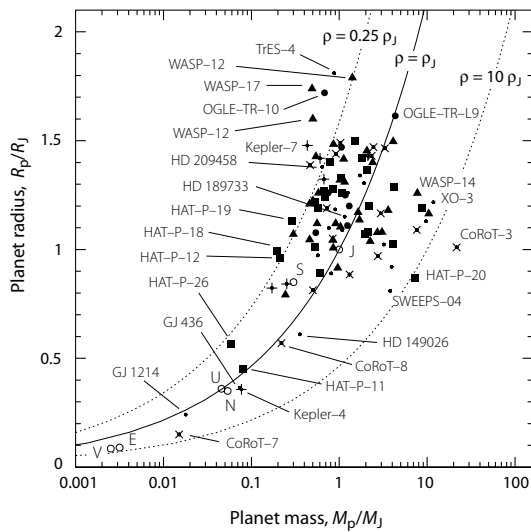


Figure 6.99: Mass–radius diagram for transiting exoplanets (● OGLE, ▲ WASP, ■ HAT, × CoRoT, + Kepler, · other). Data are from *exoplanet.eu*, 2010 November 1 (Appendix D). V, E, J, S, U, N indicate positions of Venus, Earth, Jupiter, Saturn, Uranus, Neptune. Dashed lines are of constant density in Jovian units ( $0.25, 1, 10\rho_J$ ). CoRoT-3 b ( $22M_J$ ) is a brown dwarf.

**Highest mass transiting planets** Estimates of  $R_p$  for two high-mass transiting objects provided the first constraints on the mass–radius relation for this cool, dense, and partially degenerate substellar regime. Thus CoRoT-3 b, ‘the first secure inhabitant of the brown-dwarf desert’, could either be a brown dwarf of solar composition and age 2 Gyr, or an irradiated and inflated planet with a rocky core (Deleuil et al., 2008). From their models with different metallicities, Baraffe et al. (2008) argued that, for its inferred age of 2–3 Gyr, HAT-P-2 b is too dense to be a brown dwarf. This showed, in turn, that planets can form with masses at least up to  $9M_J$ . At the same time, it requires  $\geq 200M_{\oplus}$  of heavy material in its interior, at the limit of core-accretion model predictions.

**Theoretical models** Planets from terrestrial mass upwards are expected to be primarily composed of four successive layers in differing proportions (§11.2): an iron/nickel core, a silicate (rock) layer, an ‘ice’ layer, and a H/He envelope. The mass–radius relation follows from the relevant (pressure versus density) equation of state, along with equations describing mass conservation, energy conservation, and hydrostatic equilibrium.

Amongst early models for giant planets (§11.3.3) and super-Earths (§11.3.5), Fortney et al. (2007b) computed radii for masses in the range  $0.01M_{\oplus} - 10M_J$  for pure iron, rock, water, and H/He, as well as various mixtures. They included a dependency on orbital distance in the range 0.02–10 au, coupling planetary evolution to stellar irradiation through a non-grey radiative-convective equilibrium atmosphere model. Baraffe et al. (2008) pre-

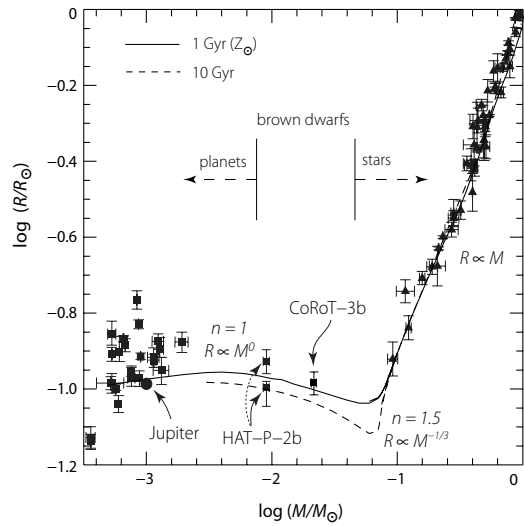


Figure 6.100: Mass–radius relation for stars and planets. Solid and short-dashed lines are models with solar composition for two isochrones, and  $n$  indicates the relevant polytropic index. Lines demarcating planets and stars are somewhat arbitrary. The CoRoT-3 b radius is from Deleuil et al. (2008). For HAT-P-2 b, both the original determination (lower point, Bakos et al., 2007a) and a later revision (upper point, Pál et al., 2010) are shown. Adapted from Chabrier et al. (2009, Figure 2).

sented similar grids of planetary evolution models from  $10M_{\oplus} - 10M_J$ , with various fractions of heavy elements.

**Planet composition** Such models show that a planet’s position in the mass–radius diagram provides an indication of its overall composition, with temperature playing a relatively minor role. GJ 436 b, for example, is a  $23M_{\oplus}$  planet comparable to Neptune in mass and radius, orbiting an M dwarf (Gillon et al., 2007b). Its position in the model grid of Fortney et al. (2007b) suggests that it is an ice giant like Uranus and Neptune, composed largely of water ice (Figure 6.101). Its high equilibrium surface temperature, between 520–620 K, would imply a steam atmosphere. It may possess a H/He envelope, of an extent which depends on the presence of an iron/rock core, and which could be retained over long time scales, despite evaporation, because of the small size and low temperature of the primary star (Lecavelier des Etangs, 2007). *In situ* formation of an ice giant so close to its parent star is considered implausible. It presumably formed at a large orbital radius, beyond the ‘snow line’ where the protoplanetary disk is cool enough for water to condense, before migrating inwards to its present position.

**Observed correlations** Despite the wide range of properties of the transiting planets, presumably reflecting their own atmosphere, interior structure, and accretion and migration history, a number of correlations have been reported. Some early inferences were based on subsets of transiting planets subjected to a uniform



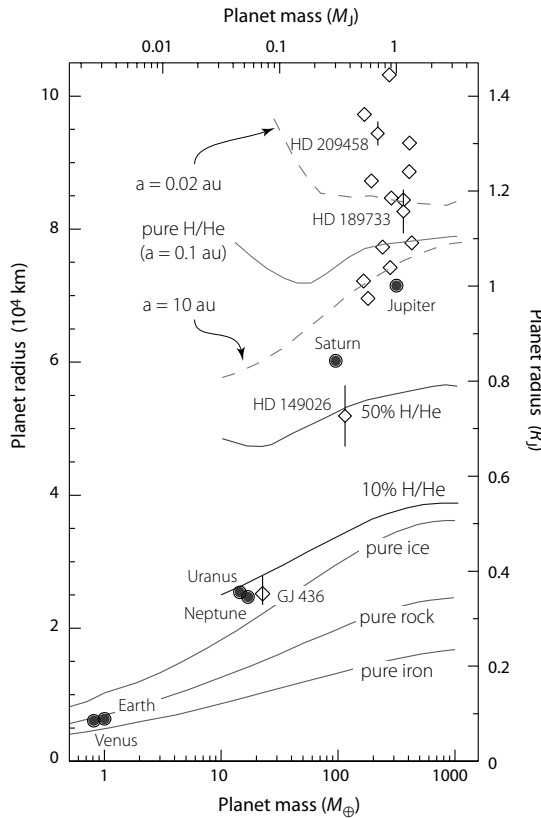


Figure 6.101: Mass–radius diagram from the Fortney et al. (2007b) models, showing the position of the first transiting hot Jupiters (diamonds) and solar system planets. Models are for pure iron, silicate, and water ice, along with 10%, 50% and 100% H/He atmospheres irradiated at 0.1 au from a solar-type star. Dotted lines are for a cold ( $a = 10$  au) and hot ( $a = 0.02$  au) pure H/He gas giant. From Gillon et al. (2007b, Figure 3), reproduced with permission © ESO.

re-analysis. Thus Torres et al. (2008) derived the host star properties  $M_\star$  and  $R_\star$  based on stellar evolution models, incorporating the transit constraint on the stellar density,  $\rho_\star$  (§6.13.7). Southworth et al. (2007) and Southworth (2008) determined a uniform set of surface gravities for 14 of the objects from their transit light curves and their stellar spectroscopic orbits (§6.13.7). These various correlations, along with a possible correlation between stellar  $T_{\text{eff}}$  and  $R_p$ , have also been investigated in a wide simulation of the CoRoT observations (Fressin et al., 2009). The effects of metallicity are considered in more detail in §8.4.

**Mass versus period** Zucker & Mazeh (2002) pointed out a correlation between planet mass and orbital period for the 70 or so planets known at the time, manifested as a paucity of massive planets with short orbital periods. Over the much narrower domain of mass and radius occupied by the transiting planets, a decrease-

ing linear relation between mass and period was found by Mazeh et al. (2005), and subsequently confirmed by others (e.g. Hansen & Barman, 2007; Torres et al., 2008; Southworth, 2009, 2012).

Two possible explanations for this correlation have been proposed: the trend for larger masses at shorter orbital periods could be related to the mechanism that halts migration, with larger planets able to migrate further in. The metallicity dependence would then imply that planets in metal-poor systems must be more massive to migrate to the same inward point compared with more metal-rich planets.

Sozzetti et al. (2006a) suggested that a dependency of migration on metallicity could arise from slower migration rates in metal-poor disks (Livio & Pringle, 2003; Boss, 2005), or through longer time scales for giant planet formation around metal-poor stars, which would reduce the migration efficiency before the disk dissipates (Ida & Lin, 2004b; Alibert et al., 2005a).

Alternatively, the mass–period relation may reflect the survival prospects close to the star, due to thermal evaporation driven by the ultraviolet flux (Baraffe et al., 2004; Mazeh et al., 2005; Davis & Wheatley, 2009; Lammer et al., 2009b). In this picture, planets with initial masses below some critical value expand as they evaporate, speeding up the evaporation process. If metal-rich planets are more likely to develop a rocky core (Pollack et al., 1996; Guillot et al., 2006; Burrows et al., 2007a), and if the presence of such a core slows down evaporation (Baraffe et al., 2004; Lecavelier des Etangs et al., 2004), then survival at a given period would have a dependence on metallicity.

**Bimodal distribution in radius** Youdin (2011b) considered four planet samples, divided between shorter and longer periods at 7 d, and between large and small radii at  $3R_\oplus$ . The size distribution showed a deficit of  $\sim 3R_\oplus$  planets at the shortest periods, suggestive of preferential evaporation and sublimation of Neptune- and Saturn-like planets, as expected in models of core accretion and migration.

Fulton et al. (2017) used the size distribution of 2025 Kepler planets (with  $P < 100$  d) to identify a factor 2 deficit in the occurrence rate at  $1.5 - 2.0R_\oplus$ , supporting the emerging picture that close-in planets smaller than Neptune are composed of rocky cores with  $R_p < 1.5R_\oplus$ , with varying amounts of low-density gas that determine their total sizes. Interpretation in terms of photoevaporation is detailed in Section 6.27.5.

**Radius versus period** Helled et al. (2016) noted a possible correlation between planetary radius and orbital period for planets with  $R_p < 4R_\oplus$ , originating from a power-law dependence between the two quantities for intermediate periods (3–100 d), combined with a dearth of planets with  $R_p > 2R_\oplus$  at short periods.

**Radius versus equilibrium temperature** Mancini (2017) identified a correlation between  $R_p$  and  $T_{eq}$ , particularly pronounced for  $M_p$  in the range  $0.5 - 1.0M_J$  and  $1.0 - 1.5M_J$ .

**Sub-Jovian desert** Reference to a *sub-Jovian desert* was made by Szabó & Kiss (2011). Benítez-Llambay et al. (2011) found that, with the exception of CoRoT-7 b, the orbital periods of close-in planets with  $M_p \geq 1M_J$  was restricted to  $P \geq 1$  d, while smaller masses were detected only down to  $P \sim 3$  d.

From the period–radius distribution of both confirmed and Kepler candidates, Beaugé & Nesvorný (2013) found a paucity, among confirmed planets, with  $3 < R_p < 10R_\oplus$  and  $P \lesssim 2 - 3$  d, which they described as the ‘sub-Jovian pampas’. The same trend is seen in multi-planet candidates, although the conclusions are sensitive to the assumed rate of false-positives.

Subsequently, as the population of small mass Kepler planets increased, a significant population of small super-Earth planets has been detected around solar-type stars with smaller orbital periods, also down to  $P \sim 1$  d and below, while the absence of very hot sub-Jovian planets remains, and increasingly better characterised (e.g. Colón et al., 2015; Mazeh et al., 2016). One candidate for the sub-Jovian desert is K2-22, the disintegrating rocky planet candidate (§6.14.21).

There may not be a single origin of this dearth of planets. Since it corresponds to the size range in which a planet would need to have significant volatiles to match the observed radius, it could be related to the effect of atmospheric evaporation which is expected to be especially effective in planets with large gas envelopes and low surface gravity (Youdin, 2011b), to the existence of an inner cavity in the protoplanetary disk acting as a planetary trap for type I migration (Benítez-Llambay et al., 2011), or to long-term tidal effects for sub-Jovian planets with large cores and light atmospheres (Beaugé & Nesvorný, 2012; Matsakos & Königl, 2016).

**Surface gravity versus period** A related correlation is that of planetary surface gravity versus orbital period (Southworth et al., 2007; Hansen & Barman, 2007; Southworth, 2008). This has been confirmed from the uniform treatment of the 22 systems considered by Torres et al. (2008), and the 14 systems considered by Southworth (2009). Since  $g_p$  can be derived from transit measurements independently of the mass or radius of the host star (§6.13.7), it should be free of possible systematics arising from stellar evolutionary models.

The  $g_p - P$  correlation may point more directly to the underlying effect responsible for the  $M_p - P$  correlation, since surface gravity is a fundamental parameter entering into the evaporation of planetary atmospheres. If metallicity influences planetary radii, and given that  $g_p \propto M_p/R_p^2$ , metallicity must also introduce some scatter into the  $g_p - P$  correlation. Fressin et al. (2009) at-

tributed part of the effect to the decreasing transit probability, and decreasing detection efficiency, for larger  $P$  and higher  $g_p$ .

### 6.27.1 Small-radii Kepler planets

Of the 2300 or so confirmed Kepler planets, a little more than 2000, or nearly 90%, have radii  $R_p \leq 4R_\oplus$ . Planetary interior models show that warm planets of this size are *gas-poor*, defined by Lissauer et al. (2014a) as composed of less than 50% H/He by mass.

Transit surveys provide strong physical diagnostics because their radii are very sensitive to small amounts of gas in the atmosphere (e.g., 1% H/He added to a  $1M_\oplus$ ,  $1R_\oplus$  solid core can inflate the planet to  $2R_\oplus$ ; Lopez & Fortney 2014) and moderately sensitive to the core’s bulk composition (e.g., H<sub>2</sub>O versus rock).

These small Kepler planets sample a wide range of incident fluxes, and have presumably been subject to a wide range of photoevaporation rates. Many are found at short orbital periods, allowing mass measurements or upper limits through radial velocity studies (Marcy et al., 2014), while some are found in compact systems with multiple transiting, low-density planets, whose short orbital periods and large radii allow sensitive mass measurements through transit time variations (§6.20).

Nevertheless, information such as the mean density is difficult to acquire since the overwhelming majority of the stars in the Kepler field are rather faint, making radial-velocity follow up observationally expensive. Barring (near-)resonant systems, where transit timing variations can be significant (Holman & Murray, 2005), this means that the masses of most planets within the Kepler sample are observationally unconstrained.

Figure 6.102 shows the masses, radii and incident flux for the subset of planets with  $M_p \lesssim 20M_\oplus$ , where those of sub-Saturn mass are dominated by Kepler discoveries.

The wide range in size of gas-poor planets of a given mass indicates a diversity of composition, which can be affected by various processes (Lissauer et al., 2014a). These include (Figure 6.103) coagulation from volatile-rich or volatile-poor planetesimals, gas accretion from the protoplanetary nebula before dispersal, outgassing of volatiles from the planet’s interior, atmospheric escape (e.g., via photoevaporation), tidal forces, and erosion or enrichment of the atmosphere and mantle via collisions with planetesimals.

**Small-radii gas-poor planets: individual** Several of the planets noted on page 179, and highlighted in Figure 6.102, have served as case studies to illustrate the properties of gas-poor planets. In particular, they sample a continuum of photoevaporation rates, which are a function of both incident stellar flux (as a proxy for the X-ray/ultraviolet radiation responsible for atmospheric erosion) and core mass. Examples include:

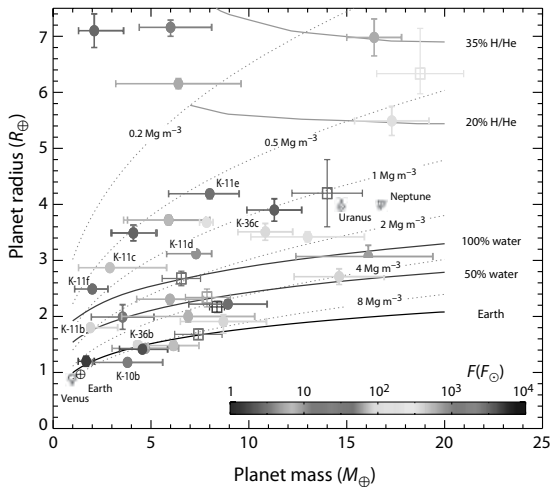


Figure 6.102: Mass–radius diagram for low-mass transiting planets,  $M_p < 20M_\oplus$ , with models for different compositions. Planets are grey-scale-coded (colour in the original) by the incident bolometric flux. Kepler planets are shown as filled circles, others by open squares. Rocky planets, at lower left, include Kepler–10 b and Kepler–36 b. The lower curve is for an Earth-like composition with 2/3 rock and 1/3 iron by mass. All others use thermal evolution models (Lopez et al., 2012), assuming an atmosphere of H/He or  $H_2O$  above a core of Fe/rock with composition as for the bulk Earth. Two curves give loci for 50% and 100%  $H_2O$  by mass, and the two upper curves are for 20% and 35% H/He atmospheres over Earth-composition cores. Theoretical curves assume a radiation flux  $100\times$  larger than that at Earth, and an age of 5 Gyr. From Lissauer et al. (2014a, Figure 2), by permission from Nature/Springer/Macmillan Ltd, ©2014.

**Kepler–11:** the middle four planets of the 6-planet system, containing 4–15% H/He by mass, might represent the non-eroded initial compositions of gas-poor planets, whereas the innermost, Kepler–11 b, is only 0.5% H/He by mass (or maybe devoid of light gases entirely if  $H_2O$ -rich), perhaps because of significant mass loss from its primordial atmosphere (Lissauer et al., 2013).

**Kepler–10:** with an incident flux about 30 times that of Kepler–11 b, Kepler–10 b may have lost all its atmosphere through photoevaporation. This speculation is based on its density, which can be matched by theoretical models that do not require a volatile component (Batalha et al., 2011). In addition to lifetime-integrated X-ray and ultraviolet flux, core mass is an important factor in determining the photoevaporation rate.

**Kepler–36:** a larger core mass for Kepler–36 c may have enabled it to maintain its atmosphere against photoevaporation, which may have stripped its companion Kepler–36 b (Lopez & Fortney, 2013).

**Small-radii gas-poor planets: statistical** Most of the gas-poor Kepler planets have masses that are less precisely measured, but nonetheless statistically significant when analysed as an ensemble.

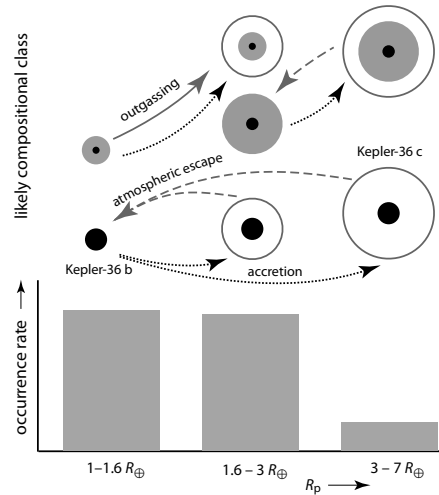


Figure 6.103: Schematic illustration of plausible compositions of the small and mid-sized Kepler planets, including rock (black), water (grey), and light gases (white), as a function of planet radius. The histograms indicate their approximate relative occurrences (Dong & Zhu, 2013; Fressin et al., 2013; Pettigura et al., 2013b). Arrows indicate physical processes that control or modify their compositions. The smallest planets, to the left, can be rocky, or possibly mixtures of rock and  $H_2O$ . Somewhat larger planets have, by volume, significant amounts of constituents less dense than rock. Planets with  $R_p > 3.8R_\oplus$ , comparable to or larger than Neptune, have envelopes composed of H and He. From Lissauer et al. (2014a, Figure 3), by permission from Nature/Springer/Macmillan Ltd, ©2014.

Furthermore, theoretical models imply that radii of warm planets in the size range  $2 - 4R_\oplus$  depend far more on H/He percentage than on total planet mass (Lopez & Fortney, 2014). Thus, the larger sample of thousands of Kepler candidates with  $R_p < 4R_\oplus$ , even if lacking measured masses, constrain planetary occurrence rates as a function of composition, and provide correlations with properties such as the orbital period and the mass and chemical composition of the host star, which in turn constrain models for their formation and evolution.

As suggested by Lissauer et al. (2014a), various ranges in  $R_p$  may indicate different regimes for planet formation and evolution (Figure 6.103):

- $R_p \lesssim 1.6R_\oplus$ : in this range, most of the small number of transiting planets with measured masses are dense enough to be rocky; in contrast, larger planets appear to require a volatile component (Rogers, 2015). This range includes all Kepler planets with  $P < 1$  d (Sanchis-Ojeda et al., 2014). These compact planets may lack gaseous atmospheres either because they were insufficiently massive to accrete significant amounts of light gases during formation (and they never outgassed an atmosphere), or because their primordial atmospheres were removed by giant impacts or photoevaporation.
- $1.6R_\oplus \lesssim R_p \lesssim 3R_\oplus$ : in this range, the mass–radius re-

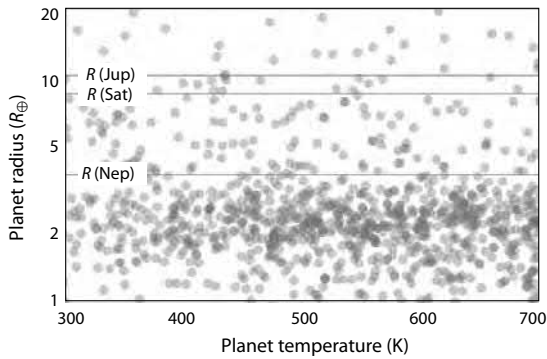


Figure 6.104: Planet radii as a function of planetary equilibrium irradiation temperature,  $T_{\text{eq}}$ , in the Kepler sample. There are a significant number of giant-planet-like radii,  $R_p > R_J$ , in this irradiation regime. From Batygin & Stevenson (2013, Figure 1), by permission of IOP Publishing/AAS.

lation is consistent with  $M_p \propto R_p$ , indicating that typical densities decrease with increasing size (Wu & Lithwick, 2013a). This mass–radius relation requires a substantial mass fraction of  $\text{H}_2\text{O}$ , or a small mass fraction (0.1–5%) in a H/He atmosphere (Wu & Lithwick, 2013a; Weiss & Marcy, 2014). Scatter in the mass–radius relation exceeds the measurement errors (Weiss & Marcy, 2014) indicating diversity in composition and/or atmospheres. A H/He atmosphere substantially increases the temperature at the rocky surface, thus planets such as Kepler–22 b, with  $R_p = 2.4R_\oplus$  (Borucki et al., 2012), are unlikely to be habitable.

- $3R_\oplus \lesssim R_p \lesssim 7R_\oplus$ : planets in this size range are less dense than water, implying extended H/He atmospheres (Wu & Lithwick, 2013a). The occurrence rate drops steeply between  $2 - 3R_\oplus$  (Petigura et al., 2013b; Morton & Swift, 2014), and only a relatively few examples are known. Few planets in this class have been found around low-mass stars (Wu & Lithwick, 2013a), perhaps suggesting a difficulty in accreting H/He envelopes in a protoplanetary disk with a low surface density of solids.
- $R_p \gtrsim 4R_\oplus$ : large planets are more common around stars with higher metal abundance (Buchhave et al., 2012), perhaps again suggesting a difficulty in accreting H/He envelopes in a protoplanetary disk with a low surface density of solids.

### 6.27.2 Low-mass gaseous Kepler planets

The Kepler data set contains a sizeable number of low-mass objects characterised by radii similar to (and in a few cases substantially exceeding) that of Jupiter (cf. §6.26.1), but only modest levels of stellar irradiation,  $200 \lesssim T_{\text{eq}} \lesssim 800 \text{ K}$ , so quite distinct from the well-known ‘hot Jupiters’ (§6.28). Batalha et al. (2013) found that, of 1333 planetary *candidates* in this  $T_{\text{eq}}$  range, 68 have  $0.9R_J \lesssim R_p \lesssim 2R_J$ , and 25 have  $R_p \gtrsim 2R_J$  (Figure 6.104).

With the exception of a few, their physical nature, and specifically their average densities, are largely unknown.

Theoretical models have long predicted that giant planets of some hundreds of  $M_\oplus$  can have large radii, that exhibit only weak dependence on mass, but are instead primarily controlled by their chemical composition and interior thermal state (Zapolsky & Salpeter, 1969; Stevenson, 1982b). The radii of these gaseous planets can increase with decreasing mass, due to the associated softening of the equation of state (Stevenson, 1982b). Whether the radius actually increases or decreases with mass, and the extent to which it does so, is sensitive to chemical composition and the degree of stellar irradiation (Fortney et al., 2007a).

In extreme proximity to the host star, the predicted upturn in radius is pronounced. Thus an evolved  $20M_\oplus$  planet irradiated at  $T_{\text{eq}} \approx 1300 \text{ K}$  is roughly twice as large as its isolated counterpart (Baraffe et al., 2008). Depending on planet age, at even higher temperatures ( $T_{\text{eq}} \sim 2000 \text{ K}$ ), the discrepancy may be a factor of a few (Guillot, 2005). At the other extreme, planetary radii at  $T_{\text{eq}} \lesssim 100 \text{ K}$  do not differ significantly from those of isolated objects (Fortney et al., 2007a). Between these extremes, with the exception of only a few studies (e.g. Rogers et al., 2011), this regime is largely unexplored.

The chemical composition of these planets is generally not well known. However, the relatively low densities of some of the well-characterised Kepler subset suggests that low overall metallicities cannot be excluded.

**Kepler–30 d** A representative example is Kepler–30 d (Batalha et al., 2013; Sanchis-Ojeda et al., 2012),  $M_p = 23.1 \pm 2.7 M_\oplus$ ,  $R = 8.8 \pm 0.5 R_\oplus$ ,  $T_{\text{eq}} = 364 \text{ K}$  (assuming zero albedo) and  $2.0 \pm 0.8 \text{ Gyr}$ , considered in detail by Batygin & Stevenson (2013). With the knowledge of the equation of state and an assumed radiative structure of the atmosphere, the construction of a static interior model is relatively straightforward. This is however not enough, since the thermal state of the planet changes in time due to radiative losses of the interior entropy (Guillot, 1999b). By extension, the planetary radius also contracts. Thus, in order to obtain definitive results that are characteristic of multi-Gyr old planets, evolutionary calculations of planetary structure are required.

Their numerical simulations of planetary thermal evolution showed that Kepler–30 d appears to be strongly deficient in heavy elements, especially compared with its solar system counterparts, and with a dominantly gaseous interior structure. More generally, they showed that  $10 - 20M_\oplus$ , Gyr-old planets, composed of high density cores and extended H/He envelopes, can have radii in the giant planet range, and which are stable against extreme ultraviolet radiation, as well as Roche lobe overflow mass-loss (Figure 6.105).

**Models of the Jupiter-radii planets** Simulations by Batygin & Stevenson (2013) were made to establish the

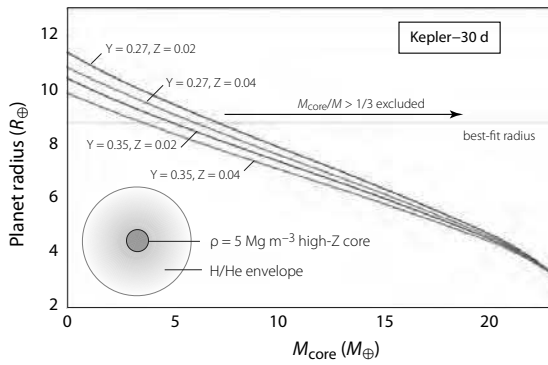


Figure 6.105: The  $R_p$ – $M_{\text{core}}$  relation for Kepler-30 d ( $M_p = 23.1M_{\oplus}$ ,  $T_{\text{eq}} = 364$  K, age = 2 Gyr), assuming various envelope compositions with  $Z = 0.02$  and  $Z = 0.04$  as indicated. The schematic at bottom-left represents a (scaled) two-layer interior model with a  $5M_{\oplus}$  core. From Batygin & Stevenson (2013, Figure 2), by permission of IOP Publishing/AAS.

range of compositions that these low-mass Jupiter-radii Kepler planets might represent. The resulting mass–radius relationships for planets with core masses of 1, 3 and  $5M_{\oplus}$  are given in Figure 6.106.

Their results highlight the fact that, accounting for stellar irradiation, giant planet radii can persist to very low masses,  $M_p \lesssim 10M_{\oplus}$ , with the behaviour largely dictated by the associated core mass. All models with a  $5M_{\oplus}$  core are stable against evaporation, and roughly follow the cold (i.e., isolated) mass–radius relationship. On the contrary,  $1M_{\oplus}$  core models are largely unstable below  $M_p \lesssim 15M_{\oplus}$ , but can have radii comparable to that of Jupiter prior to the onset of evaporation. A similar scenario is observed for the  $3M_{\oplus}$ ,  $T_{\text{eq}} = 500$  K set of models. These models are essentially always characterised by  $R_p \approx R_J$  above  $M_p \gtrsim 8M_{\oplus}$ .

Some models (e.g., those corresponding to 1 and  $3M_{\oplus}$  and  $T_{\text{eq}} = 700$  K) have  $R_p > R_J$ , due to the softening of the equation of state at lower pressures. Although reminiscent of the inflated radii of hot Jupiters (§6.28.4), these objects are fundamentally different, requiring no additional heat sources, or other mechanisms for halting gravitational contraction.

### 6.27.3 Mass and radius estimation

While some dozens of Kepler planet masses have been determined via radial velocity follow-up, the majority of Kepler host stars are too faint to permit such direct mass estimates to be made. Over 100 have been estimated from transit time variations (§6.20).

For their dynamical studies, Lissauer et al. (2011b) estimated masses from the Kepler-measured radii as

$$M_p = \left( \frac{R_p}{R_{\oplus}} \right)^{2.06} M_{\oplus}, \quad (6.160)$$

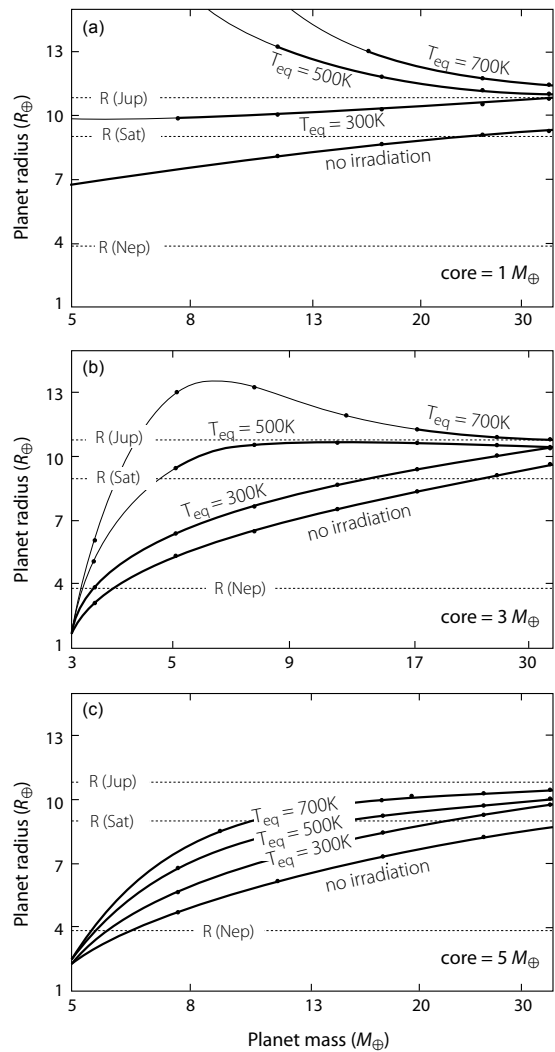


Figure 6.106: Mass–radius relationships of the low-mass, gas-dominated planet models of Batygin & Stevenson (2013). Panels a, b, and c correspond to planets with core-masses of 1, 3 and  $5M_{\oplus}$  respectively. Mass–radius relationships are shown corresponding to  $T_{\text{eq}} = 300$ , 500 and 700 K. Thick lines run through models that are stable against evaporation, while the converse is true for thin lines. Lower lines in each panel are the isolated mass–radius relationships. Radii characteristic of giant planets are readily attainable for mildly irradiated  $M \sim 10M_{\oplus}$ ,  $M_{\text{core}} = 1, 3M_{\oplus}$  planets. From Batygin & Stevenson (2013, Figure 3), by permission of IOP Publishing/AAS.

where the power-law exponent was obtained by fitting to Earth and Saturn; it slightly overestimates the mass of Uranus ( $17.2M_{\oplus}$  versus  $14.5M_{\oplus}$ ) and slightly underestimates the mass of Neptune ( $16.2M_{\oplus}$  versus  $17.1M_{\oplus}$ ).

Observations of transiting exoplanets (Lissauer et al., 2011a, and references) show more significant deviations, with both denser and less dense planets known but, on average, exoplanets smaller than Saturn are con-

sistent with this trend.

A relationship for estimating the radii of planets of known mass, derived as a fit to the solar system planets as well as transiting exoplanets of known mass, was proposed by Tremaine & Dong (2012, eqn 47)

$$\log\left(\frac{R_p}{R_j}\right) = 0.087 + 0.141 \log\left(\frac{M_p}{M_j}\right) - 0.171 \left[ \log\left(\frac{M_p}{M_j}\right) \right]^2. \quad (6.161)$$

This increases monotonically up to  $\sim 1M_j$ , with a relatively constant radius for higher mass. It follows that  $M_p$  cannot be derived from  $R_p$  at higher mass.

Bashi et al. (2017) gave the empirical mass–radius relation  $R \propto M^{0.55 \pm 0.02}$  for small planets ( $M_p < 124 \pm 7M_\oplus$  and  $R_p < 12.1 \pm 0.5M_\oplus$ ) and  $R \propto M^{0.01 \pm 0.02}$  for large planets, where the break point is linked to the onset of electron degeneracy in H, and therefore to the planetary bulk composition. Specifically, it is the characteristic minimal mass of a planet that consists of mostly H/He, with a mass–radius relation determined by their equation of state.

Chen & Kipping (2017) developed a probabilistic mass–radius forecasting model over nine orders of magnitude in mass, *Forecaster*, conditioned on a sample of 316 well-constrained objects spanning dwarf planets to late-type stars, classified as ‘Terran’, ‘Neptunian’, ‘Jovian’, and stars. A transition in the mass–radius relation at  $2.0^{+0.7}_{-0.6}M_\oplus$  is associated with the divide between solid (Terran) worlds and Neptunian worlds.

#### 6.27.4 Minimum densities from the Roche radius

Planets with very short orbital periods, including the 70 or so Kepler planets with  $P \leq 1$  d, essentially all have  $R < 2R_\oplus$ . There are various reasons why the larger gas giants are unlikely to survive in such short-period orbits, including tidally-induced orbit decay (Rasio & Ford, 1996); a possible tidal-inflation instability (Gu et al., 2003b); Roche lobe overflow (Gu et al., 2003a); and evaporation (Murray-Clay et al., 2009).

An Earth-mass rocky planet would be less susceptible to these effects, and in particular the solid portion of the planet could survive evaporation nearly indefinitely (Perez-Becker & Chiang, 2013). However, even small planets must orbit outside of the Roche radius, the distance within which the tidal force from the star would disrupt the planet’s hydrostatic equilibrium and cause it to rapidly disintegrate (Rappaport et al., 2013).

For a body comprised of an incompressible fluid with negligible bulk tensile strength in a circular orbit about its parent star, the Roche limiting distance is

$$a_{\min} \approx 2.44R_\star \left( \frac{\rho_\star}{\rho_p} \right)^{\frac{1}{3}}, \quad (6.162)$$

where  $\rho_\star$  and  $\rho_p$  are the mean densities of the parent star and of the planet, respectively, and  $R_\star$  is the radius

of the parent star. In cases where  $P$  is measured directly, the equation can be rewritten using Kepler’s third law,  $(2\pi/P)^2 = GM/a^3$ . The stellar mass and radius cancel, to give the minimum orbital period before the planet is tidally disrupted (Rappaport et al., 2013, eqn 2)

$$P_{\min} \approx \left( \frac{3\pi (2.44)^3}{G\rho_p} \right)^{\frac{1}{2}} \approx 12.6 \text{ hr} \left( \frac{\rho_p}{1 \text{ Mg m}^{-3}} \right)^{-\frac{1}{2}}. \quad (6.163)$$

$P_{\min}$  is essentially independent of the properties of the parent star (except if it is rapidly rotating and substantially oblate), and depends only on  $\rho_p$ . The expression can be rearranged to place a lower limit on the planet’s mean density for a given orbital period.

For a highly compressible fluid composition, the analogous result is (Rappaport et al., 2013, eqn 4)

$$P_{\min} \approx \left( \frac{3\pi}{(0.49)^3 G\rho_p} \right)^{\frac{1}{2}} \approx 9.6 \text{ hr} \left( \frac{\rho_p}{1 \text{ Mg m}^{-3}} \right)^{-\frac{1}{2}}. \quad (6.164)$$

Planets composed of iron and silicates are neither of uniform density nor highly compressible, and for this regime interpolation gives Rappaport et al. (2013, eqn 5)

$$P_{\min} \approx 12.6 \text{ hr} \left( \frac{\rho_p}{1 \text{ Mg m}^{-3}} \right)^{-\frac{1}{2}} \left( \frac{\rho_{0p}}{\rho_p} \right)^{-0.16}, \quad (6.165)$$

where  $\rho_{0p}$  is the central density of the planet. For the planets of interest, the ratio of central density to mean density,  $\rho_{0p}/\rho_p$ , ranges between  $\sim 1$ –2.5.

Applied to Kepler–974 c, an unconfirmed  $0.63R_\oplus$  planet with one of the shortest orbital periods,  $P = 4.25$  h (Ofir & Dreizler, 2013), Rappaport et al. (2013) infer a mean density  $\rho \geq 7 \text{ Mg m}^{-3}$ . Models of the planetary interior then suggest that the planet must be mainly Fe, with at most a modest fraction of silicates.

Sanchis-Ojeda et al. (2014) applied this to derive lower density limits for their short-period planet sample and, using  $R_p$  from transit measurements, lower limits on  $M_p$ , with constraints on the mean density of 10 terrestrial-sized planets. For the few with  $P < 5$ –6 h,  $P_{\min}$  suggests that the planets are likely to be rocky.

#### 6.27.5 Effects of photoevaporation

Lopez & Fortney (2013) derived analytic fits to atmospheric loss rates as a function of extreme ultraviolet irradiation, and the planet’s core mass and composition. They suggest that photoevaporation provides a natural explanation for the findings that, within multi-planet systems, inner planets are preferentially smaller (S6.30), and predict that  $1.8$ – $4R_\oplus$  planets should be significantly less common on orbits with  $P < 10$  d.

Owen & Wu (2013) found that photoevaporation significantly affects only low mass planets with H envelopes, being able to remove massive H envelopes inward of  $\sim 0.1$  au for lower mass (Neptune-mass) objects.

They found that evaporation is negligible for Jupiter-mass objects. They concluded that evaporation is a driving evolutionary force for close-in Kepler planets, and that some 50% may have been significantly eroded.

From the bimodal distribution of radii established for 2025 Kepler planets by Fulton et al. (2017), a detailed explanation in terms of photoevaporation was given by Owen & Wu (2017). Qualitatively, the time scale for envelope erosion is the longest for those planets with H/He-rich envelopes which, while only a few percent in weight, can double its radius. The time scale falls for lighter envelopes because the  $R_p$  remains largely constant for tenuous envelopes. The time scale also drops for heavier envelopes because the planet swells up faster than the addition of envelope mass. Photoevaporation therefore herds planets into either bare cores ( $\sim 1.3R_\oplus$ ), or those with double the core radius ( $\sim 2.6R_\oplus$ ). This process mostly occurs during the first 100 Myr when the stars' high-energy fluxes are high and nearly constant.

The population of ultra-short-period planets with  $P < 1$  d, and with typical  $R_p < 1.5R_\oplus$  suggestive of a rocky composition (§6.12.3), contrasts with the distribution out to  $P \sim 100$  d, which is dominated by low-density sub-Neptunes with  $R_p > 2.0R_\oplus$ , which must have a gaseous envelope to explain their size. The ultra-short-period planets are, again, naturally produced as the photoevaporated remnants of sub-Neptune planets with H/He envelopes (Lopez, 2017). Simulations showing that envelopes could be retained if they are formed with very high-metallicity  $H_2O$ -dominated envelopes. Their predicted sizes,  $R_p > 2R_\oplus$ , is inconsistent with the observed evaporation desert, and indicates that most ultra-short-period planets likely formed from  $H_2O$ -poor material within the snow line.

The fact that the ultra-short-period planets are likely to be the evaporated cores of sub-Neptunes rather than of hot Jupiters is supported by the metallicity differences of their host stars (Winn et al., 2017b).

## 6.28 Transiting hot Jupiters

This section covers the discovery of hot Jupiters, and their associated properties from transit observations. Other sections cover a summary of their overall occurrence rates in radial velocity and transit surveys (§1.6.2), the occurrence rates in radial velocity surveys (§2.11.4), atmospheres from transit and eclipse spectroscopy (§11.6), and current understanding of their formation (§10.7.1).

### 6.28.1 Introduction

Hot Jupiters have been discovered both from radial velocity surveys (§2.11.4), as well as from transit surveys. Their overall occurrence rates in these surveys are summarised and compared in Section 1.6.2.

Broadly, and as suggested in Section 1.6.2, hot Jupiters can be considered as Jupiter-sized planets with  $a \lesssim 0.1$  au, or  $P \lesssim 9$  d. However, the term is not well defined, there are tails in the distributions of  $a$ ,  $P$ , and  $R_p$ , and discussions and properties depend somewhat on the choice of definition.

At the end of 2017, the NASA Exoplanet Archive gave 179 objects with  $P \lesssim 10$  d and  $M_p > 1M_J$  (or  $R_p > 1R_J$ ), of which one is a pulsar (PSR J1719–14), 16 were discovered through radial velocity measures, and the remaining 160 or so from transit surveys, mostly from the HAT and WASP surveys, and with some 25 from Kepler. A few may have been misclassified (Wang et al., 2015c).

Hot Jupiters are considered to be relics of dynamical processes that shape all planetary system architectures. They are generally thought to have been transported inwards, from their formation regions much further out, by a combination of disk migration and Lidov–Kozai oscillations, and accompanied by tidal circularisation, although other origins have been considered (§10.7.1).

Hot Jupiters are generally observed to orbit their host star alone, i.e. as a single planet system (Lillo-Box et al., 2016a). Searches for other planets in the same system are detailed below. Consistent with the idea that a fraction, but not all, have formed by Lidov–Kozai oscillations with tidal friction (§10.10.6), some hot Jupiter host stars are accompanied by more distant binary companions.

Again, consistent with the idea that a fraction of hot Jupiters have been transported inwards by relatively smooth processes of disk migration, some are observed to be in orbits aligned with their host star's equatorial plane. Others are believed to have been brought inwards by Lidov–Kozai oscillations or, more violently, by planet–planet scattering, leaving signatures of such processes in the misalignment of their orbits with respect to the host star spin.

When the system is in a favourable edge-on transiting configuration, the atmosphere (and related processes) of the unseen planet can be probed by transit and eclipse spectroscopy (the principles are described in §6.24, the results in §11.6). Although the principle of transit and emission spectroscopy applies to all planets, most of those probed to date are hot Jupiters. As described in Section 11.6, there is growing evidence for hot Jupiters with various emission and absorption features, planets with featureless spectra, planets with inversion layers, and planets showing various degrees of heat redistribution between the day-side and night-sides.

**The hottest hot Jupiters** Hot Jupiters are conveniently classified in terms of their host star proximity (either via  $a$  or  $P$ ). In practice, a planet's equilibrium temperature ( $T_{eq}$ ; §6.158) is determined by its proximity to the host star, its albedo and other spin or atmospheric circulation-related effects, other heat sources including

tidal and radiogenic heating and, to a more significant extent, by the host star luminosity and spectral type.

As of the end of 2017, only a small number of planets have been found transiting A-type stars ( $T_{\text{eff}} \sim 7300\text{--}10000\text{ K}$ ), and none transiting the hotter B-type stars. Transiting planets with the highest estimated equilibrium temperatures include WASP-33 b with  $T_{\text{eq}} \sim 2710\text{ K}$  (Collier Cameron et al., 2010b), and HAT-P-7 b with  $T_{\text{eq}} \sim 2730\text{ K}$  (Pál et al., 2008).

The most extreme is KELT-9 b, in a 1.5-d orbit transiting the hottest known (A0-type,  $T_{\text{eff}} \sim 10170\text{ K}$ ) host star HD 195689 (Gaudi et al., 2017). With a day-side temperature of  $T_{\text{eq}} \sim 4600\text{ K}$ , it receives 700 times more extreme-ultraviolet radiation than WASP-33 b, implying a mass-loss rate that could leave it stripped of its envelope during the star's main-sequence lifetime (§11.4.5).

The hottest of the radial velocity hot Jupiters have  $T_{\text{eq}} \sim 500\text{--}1000\text{ K}$ , while the more massive ( $M_{\text{p}} \sim 10\text{--}20M_{\text{J}}$ ) and more distant-orbiting ( $a \sim 100\text{--}200\text{ au}$ ) planets detected by direct imaging, including GQ Lup, CT Cha and FU Tau, with  $T_{\text{eq}} \sim 2000\text{--}2500\text{ K}$ , are self-luminous rather than irradiation dominated.

### 6.28.2 Secondary eclipses

Systematic searches have been made for secondary eclipses and optical phase variations in the Kepler data, with (limits on) the secondary eclipse depth corresponding to limits on the planet's albedo (§6.24.2).

A uniform search for secondary eclipses of 76 hot Jupiters in Kepler Q2 light curves found just 6 systems detected at  $> 3\sigma$  confidence (Coughlin & López-Morales, 2012a; Rogers et al., 2013).

Esteves et al. (2013) searched for optical phase variations for all close-in candidates ( $a/R_{\star} < 10$ ) in the first 15 quarters of Kepler data. Eight systems showed significant secondary eclipses as well as phase variations, in practice nearly doubling the number of measured phase variations at the time. Their phase curve modeling (§6.15.3) included the primary transit and secondary eclipse, effects of ellipsoidal variations and Doppler beaming, derived albedos, and dayside/nightside temperatures (Figure 6.107). Their results for Kepler-13, where they detected a third cosine harmonic with an amplitude of  $6.7 \pm 0.3\text{ ppm}$ , and a phase shift of  $-1.1 \pm 0.1\text{ rad}$ , are discussed further in Section 6.14.3.

Angerhausen et al. (2015a) extended the search to the first 16 quarters of Kepler data, using a detailed phase curve model (§6.15.3), and focusing on the 20 confirmed planets out of the 489 KOIs with  $R_{\text{p}} > 4R_{\oplus}$ ,  $P < 10\text{ d}$ , and  $V < 15\text{ mag}$ .

**Secondary eclipses for super-Earths** For super-Earths, eclipses were first detected with Kepler in the two hot, close-in planets Kepler-10 b (Batalha et al., 2011) and Kepler-78 b (Sanchis-Ojeda et al., 2013a). Unlike the hot Jupiters, these two planets show relatively

high geometric albedos, between 0.3–0.6. These planets are unlikely to have substantial atmospheres at such extreme temperatures ( $> 1500\text{ K}$ ) and are possibly a new class of ‘lava ocean’ planet (Léger et al., 2011b; Rouan et al., 2011). The Kepler data set contains many super-Earths and sub-Saturn-sized candidates at slightly less extreme temperatures. At slightly lower temperatures and greater distances from the host star, the eclipse signals from these candidates are much weaker.

Demory (2014) constrained the geometric albedos for 27 super-Earth candidates in the Kepler catalogue, and found that their albedos are statistically larger than those of hot Jupiters (0.16–0.30 versus 0.06–0.11), with a subset of unusually bright candidates like Kepler-10 b, with albedos greater than 0.4. Only a few of the candidates showed significant eclipses, while the remainder of the sample gave only upper albedo limits.

Sheets & Deming (2014) approached the problem of identifying small amplitude secondary eclipses by searching an *average* light curve for multiple candidates with similar orbital and physical characteristics. The statistical method allows measurements of unbiased physical properties of Kepler's planet candidates, even for candidates whose individual signal-to-noise precludes the detection of their secondary eclipse. They detected a secondary eclipse depth of  $3.8^{+1.1}_{-1.1}\text{ ppm}$  for a group of 31 sub-Saturn ( $R < 6R_{\oplus}$ ) candidates with the greatest potential for a reflected light signature ( $(R_{\text{p}}/a)^2 > 10\text{ ppm}$ ).

**Secondary eclipse versus transit times** Time shifts between the transit times and secondary eclipse times can arise from various effects, including orbital eccentricity, surface brightness effects, and propagation delay.

A small eccentricity adds  $\sim 2Pe\cos\omega/\pi$  to the time between transit and secondary eclipse (Winn, 2010, eqn 33). Therefore a small eccentricity of  $5 \times 10^{-4}$  is enough to shift  $\Delta t$  by about 30 s, while inducing a very small difference,  $\leq 10\text{ s}$ , between the transit and occultation duration (Winn, 2010, eqn 34).

Non-uniform surface brightness affects the shape of the ingress and egress light curve, and the measured mid-occultation time when fitted with a model assuming a uniform distribution (Williams et al., 2006; de Wit et al., 2012). For example, a time shift due to an offset of the hottest region on the planetary surface from the substellar point was measured by Agol et al. (2010) for HD 189733 b at  $8\text{ }\mu\text{m}$ , attributed to super-rotating winds near the planetary equator (e.g. Showman & Guillot, 2002; Knutson et al., 2007a; Showman et al., 2009).

Propagation delays (§6.19), in which the planet is moving away from the observer during occultation ingress, and towards the observer during egress, cause the latter to appear slightly shorter than the former, and in principle affects the timing difference (Loeb, 2005).

**Secondary eclipse phase offsets** A full orbital phase curve displaying the primary and secondary eclipses offset in phase,



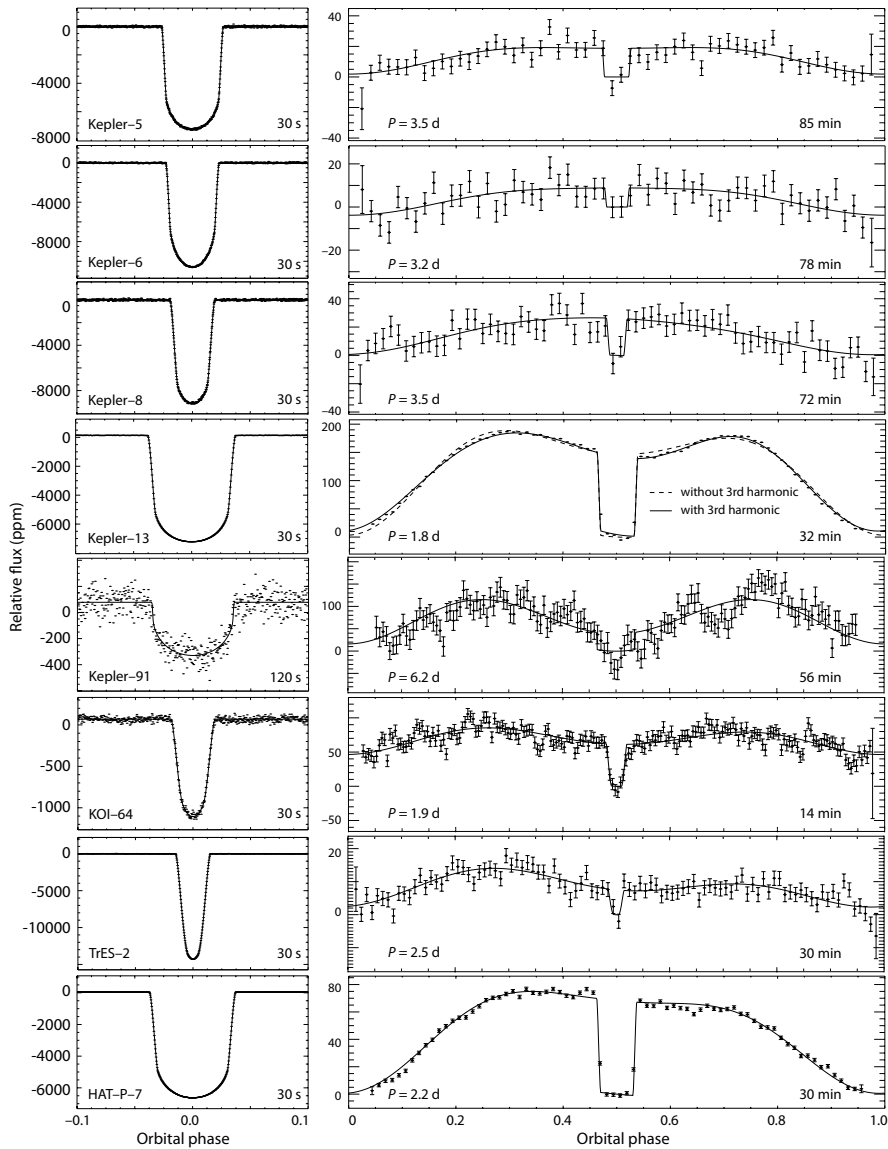


Figure 6.107: Binned and phase-folded transit curves (left) and full phase curves (right) for the 8 systems with significant secondary eclipses, and phase variations, in the first 15 quarters of the Kepler data. Models account for ellipsoidal variations and Doppler beaming.  $P_{\text{orb}}$  is given at bottom left, binning intervals at bottom right. For Kepler-13, fits are shown without (dashed) and with (solid curve) a third harmonic component. From Esteves et al. (2013, Figures 1–3), by permission of IOP Publishing/AAS.

would be an interesting illustration of a significantly eccentric orbit. Such is shown for KOI-1152 in Szabó et al. (2013, Figure 5), but this appears to be classified as a false positive. Kepler-4 shows the effect, but the secondary eclipse S/N is poor (Sheets & Deming, 2017).

### 6.28.3 Albedos

The secondary eclipse depth (or upper limits) provides limits on the planet's albedo. Most (hot) giant planets are found to have a low albedo. Pre-Kepler observations of

hot Jupiters indicate low albedos at optical wavelengths, including  $\nu$  And (Collier Cameron et al., 2002),  $\tau$  Boo (Leigh et al., 2003b), HD 209458 (Rowe et al., 2006), and others (Cowan & Agol, 2011b).

In their study of Kepler secondary phase curves and secondary eclipses, Angerhausen et al. (2015a) found that most of the massive planets in their sample have  $A_B < 0.1$ , with only a few having higher albedo. Upper limits on eclipses depths from other systems confirms the picture of generally low albedos, consistent

with predictions of theoretical atmosphere models (Sudarsky et al., 2000; Burrows et al., 2008b). Examples of higher albedos include Kepler-7 b (Demory et al., 2011b) where the occultation depth in the Kepler bandpass,  $44 \pm 5$  ppm, if directly related to the albedo, translates to a Kepler geometric albedo of  $0.32 \pm 0.03$ .

As described in Section 6.15.1, however, the effects of ‘reflection modulation’ is actually a combination of scattered light with radiation absorbed and thermally re-emitted at different wavelengths. The two processes are controlled by the Bond albedo,  $0 < A_B < 1$ , and the day-night heat redistribution efficiency,  $0 < \epsilon < 1$ , which can be constrained only if observations of the phase modulation or the secondary eclipse are available at different wavelengths (Cowan & Agol, 2011b).

For close-in lower mass super-Earths and super-Neptunes, Sheets & Deming (2017) determined average albedos from a statistical analysis of long-cadence Kepler secondary eclipse data. For three groups ( $1-2R_\oplus$ ,  $2-4R_\oplus$ ,  $4-6R_\oplus$ ), they found averages of  $0.11 \pm 0.06$ ,  $0.05 \pm 0.04$ , and  $0.23 \pm 0.11$  for the case where heat is uniformly distributed (and lower if the heat distribution is inefficient), darker than suggested by the short-cadence results, but not as dark as many hot Jupiters.

Cowan & Agol (2011b) argued that it is impossible to distinguish between reflected and re-radiated light from the single-band Kepler light curve. As an example, the Kepler light curve of HAT-P-7 can be explained as mostly reflected light at one extreme, or as mostly thermal emission at the other, with the full range of intermediate models consistent with the light curve.

#### 6.28.4 Anomalous (inflated) radii

The anomalous radii of hot Jupiters was noticed early in the study of transiting systems. Various explanations have been put forward, but no universal mechanism seems to fully account for the observed anomalies.

**Solar system anomalies** In what is referred to as the ‘anomalous radiation properties’ of the solar system giants, Jupiter and Saturn emit more radiant energy than they receive from the Sun, a factor of around 1.7 in the case of Jupiter (e.g. Low, 1966). It being argued that they are of insufficient mass to support gravitationally-induced fusion (§9.1.1), various other energy sources have been proposed. However, even for these well-studied objects, a definitive understanding of their internal heat sources remains elusive.

Proposed additional energy sources include: matter accretion during planet formation (e.g. de Pater & Lissauer, 2010); release of gravitational energy due to contraction and/or He sedimentation (Stevenson & Salpeter, 1977a; Guillot, 1999a); decay of radioactive isotopes in the core (Hubbard, 1989); high-energy deuterium Coulomb interactions (Ouyed et al., 1998; Ouyed & Jaikumar, 2016); deuterium burning (Coraddu et al., 2002); fusion of deuterons in the liquid phase of metallic deuterium (Liboff, 2007), and layered convection (Leconte & Chabrier, 2013; André et al., 2017).

**Stellar irradiation** Although early transit results for HD 209458 b showed that its radius,  $1.35R_J$ , is consistent with it being a gas giant composed primarily of H, its radius was nevertheless  $\sim 10\%$  larger than theory had predicted (Guillot et al., 1996). Such anomalies were unexpected because the mass–radius relation for giant planets was expected to be unique for a given composition (Zapolsky & Salpeter, 1969). The compensating effects of electron degeneracy and electrostatics yield a quasi-constant radius over  $1-7M_J$  (e.g. Chabrier et al., 2009).

These considerations led Burrows et al. (2000a) to conclude that HD 209458 b must have migrated inward very early on in its lifetime, such that the incident irradiation from the star inhibited the further convective cooling and contraction expected for an object of its age. But studies incorporating realistic atmospheric temperature profiles showed that models could replicate the observed radius only if the deep atmosphere is unrealistically hot (Bodenheimer et al., 2001; Guillot & Showman, 2002; Bodenheimer et al., 2003; Baraffe et al., 2003).

Many other examples of large-radius, low-density, inflated planets have since been discovered, including CoRoT-1 b (Barge et al., 2008); HAT-P-1 b (Bakos et al., 2007b); HAT-P-39 b, HAT-P-40 b, and HAT-P-41 b (Hartman et al., 2012); Kepler-7 b (Latham et al., 2010); TrES-4 b (Mandushev et al., 2007); WASP-12 b (Li et al., 2010b); and WASP-17 b (Anderson et al., 2010b).

While models taking into account the stellar irradiation on the internal heat content can reproduce the radii of many hot Jupiters (e.g. Barman et al., 2001; Chabrier et al., 2004; Baraffe et al., 2005; Guillot, 2005; Fortney et al., 2006b; Baraffe et al., 2008; Fortney & Nettelmann, 2010; Baraffe et al., 2010; Spiegel & Burrows, 2013) others, including HD 209458 b, TrES-4 b, and various WASP objects (Ibgui et al., 2010), have radii larger than most of these predictions.

The relation between  $R_p$  and irradiation levels and orbital radius indicate that most have contracted further out before migrating inwards (Donnison & Williams, 2014; Yıldız et al., 2014). Irrespective of the energy deposition, generalised analytical cooling estimates, including the effects of convective regions, have been presented by Ginzburg & Sari (2015).

**Other explanations** Other effects have been suggested to introduce or maintain heat in the planetary interiors, although no single phenomenon appears able to reproduce all planets with inflated radii. They can be broadly divided into two main categories: models that directly inflate planetary radii (either by depositing a fraction of the incident irradiation into the interior, or by invoking other heat sources), and models that simply slow a planet’s radiative cooling, allowing it to retain more heat from formation and thereby delay contraction. The following suggested mechanisms are ordered roughly chronologically to illustrate the development.

**Detailed suggestions** Tidal heating due to orbit circularisation by the host star provides an additional heat source (Bodenheimer et al., 2001, 2003; Gu et al., 2004; Levrard et al., 2009; Ibgui & Burrows, 2009; Miller et al., 2009; Ibgui et al., 2010, 2011; Jermyn et al., 2017). Tidal heating through ongoing orbital circularisation resulting from perturbations due to a second planetary companion may also contribute (Bodenheimer et al., 2003; Mardling, 2007), although this was ruled out for HD 209458 b (Laughlin et al., 2005b).

Winn & Holman (2005) proposed obliquity tides, normally damped through tidal dissipation, but which may persist if the planet is in a Cassini state (a resonance between spin precession and orbital precession; §6.30.4). Later work showed that a Cassini resonance is unlikely for short-period planets (Fabrycky et al., 2007; Levrard et al., 2007; Peale, 2008).

Guillot & Showman (2002) and Showman & Guillot (2002) proposed that extra heating due to strong insolation-driven weather patterns could lead to the conversion of kinetic (wind) energy into thermal energy (forced turbulent mixing) at pressures of tens of bars. Burrows & Barman (2007) suggested that if irradiation-driven evaporation preferentially removes He, the reduction in mean molecular weight may result in anomalously large radii for a given mass. Effects on TiO and stratospheric inversions were considered by Youdin & Mitchell (2010).

Burrows et al. (2003a) argued that the size discrepancy stems from an improper interpretation of the transit radius, and that the measured radius lies higher in the planetary atmosphere than generally assumed. Burrows et al. (2007a) invoked enhanced atmospheric opacities that retain the internal heat.

Gaudi (2005) drew attention to a Malmquist-like selection effect, whereby the number of planets with radius  $R_p$  detected in a signal-to-noise limited transit survey, is  $\propto R_p^\alpha$ , with  $\alpha \sim 4 - 6$ . For a dispersion in the intrinsic distribution of planetary radii  $\sigma$ , this leads to detected planets being larger on average by a fractional amount  $\alpha(\sigma/\langle R_p \rangle)^2$  relative to the mean radius  $\langle R_p \rangle$  of the underlying distribution.

Miller et al. (2009) computed a grid of cooling and contraction paths for 45 transiting systems, starting from a large phase space of initial semi-major axes and eccentricities. Although matches can be found for a large fraction of planets with anomalously large radii, they found that orbit circularisation can be preceded by long periods when the semi-major axis is only slowly decreasing. This explanation would require that some of the systems are being viewed at privileged times of tidal evolution and hence radius inflation.

Amongst other detailed atmospheric explanations, layered convection (and the associated ‘density staircases’) in atmospheres characterised by molecular weight gradients decreases heat loss and slows down contraction in the planetary interior (Chabrier & Baraffe, 2007; Leconte & Chabrier, 2013; Kurokawa & Inutsuka, 2015; André et al., 2017).

Tremblin et al. (2017) proposed the advection of the *potential temperature* (their equation 2), a process occurring in the Earth’s atmosphere or oceans, by which atmospheric circulation induces a vertical mass flux in the deep atmosphere, advecting the potential temperature in a region of small heating rate, and imposing a hot adiabatic interior.

Without specifying the unknown heating mechanism, Komeck & Youdin (2017) showed that deeper atmospheric heating, at  $\sim 10^7$  Pa, requires heating at only 1% of the stellar irradiation to explain the radius of HD 209458 after 5 Gyr of cooling. Jermyn et al. (2017) showed that a combination of tidal models incorporating thermal feedback, coupled with heat trapping at depth, leads to entropy increase in the central convective region

and expansion of the planet’s radius.

Electrical current generated through the interaction of atmospheric wind-driven ionised particles with the planetary (and stellar) magnetic field can provide an additional heat source through Ohmic dissipation in the deepest atmospheric layers, reaching  $\sim 1\%$  of that from stellar insolation (Laine et al., 2008; Batygin & Stevenson, 2010; Perna et al., 2010a,b; Batygin et al., 2011c; Laughlin et al., 2011; Chang et al., 2012; Heng, 2012b; Huang & Cumming, 2012; Menou, 2012c; Buzasi, 2013; Rauscher & Menou, 2013; Wu & Lithwick, 2013b; Bisikalo & Shematovich, 2015; Ginzburg & Sari, 2016; Pu & Valencia, 2017). Laughlin et al. (2011) found that the radius anomalies are strongly correlated with planetary equilibrium temperature, with a best-fit dependence,  $\delta R \propto T_{\text{eff}}^\alpha$ , with  $\alpha = 1.4 \pm 0.6$ .

Militzer & Hubbard (2013) revised the equation of state for relevant H/He mixtures, leading to increased radii of the hottest planets by  $\sim 0.2M_j$  (§11.3.1).

Following from models put forward to explain the heat flux of Jupiter, Ouyed et al. (1998) and Ouyed & Jaikumar (2016) invoked high-energy deuteron Coulomb interactions (DD fusion) at the core–mantle interface.

Many of these proposed mechanisms to explain inflated radii are expected to become less effective as the stellar incident flux decreases (Burrows et al., 2007a; Fortney et al., 2007b; Demory & Seager, 2011).

A test to distinguish the two main categories of inflation models (excess heat deposition, or delaying its radiative cooling) was suggested by Lopez & Fortney (2016): during post-main sequence evolution, gas giants orbiting at moderate orbital periods will experience significant increases in their stellar irradiation. If hot Jupiter inflation works by depositing irradiation into the planet’s deep interiors, otherwise non-inflated gas giants at  $P \gtrsim 10$  d can re-inflate as their host stars evolve.

An explanation in terms of the affected planets being, in fact, ‘binary planets’ is discussed in Section 6.14.4.

**Insights from Kepler** Availability of the Kepler data has provided a much larger sample to probe the effect of irradiation across a wide range of orbital separations. For a sample of 138 giant planet Kepler candidates, Demory & Seager (2011) confirmed that the most irradiated transiting hot Jupiters are characterised by anomalously inflated radii, sometimes exceeding Jupiter’s size by more than 60%. They found an increase in planet radii with increased stellar irradiation. In the case of only modest irradiation, radii are not inflated, and are independent of the incident flux (Figure 6.108).

The physical mechanism(s) inflating hot Jupiters appear to become ineffective below an orbit-averaged stellar irradiation level of  $\sim 2 \times 10^5 \text{ W m}^{-2}$ . Below this threshold, the sample shows constant radii of  $\sim 0.87 \pm 0.12R_j$ , with no inflated giant planet radii, but with a scatter that could be due to the effects of metallicity. Planets enriched with heavy elements may then display a smaller radius, as has been suggested for HD 149026 b (Sato et al., 2005a).

**Small hot Jupiters** HD 149026 b was the first of several transiting giant planets found to have a radius significantly *smaller* than predicted by standard theories (Sato et al., 2005a). One explanation is that it could have

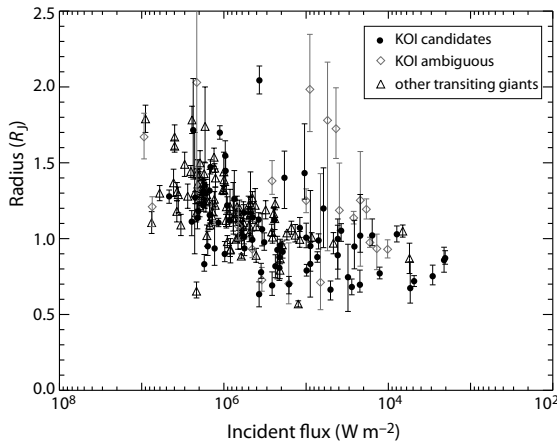


Figure 6.108: Planetary radii as a function of incident flux. Filled circles are KOIs considered as planetary candidates, while grey diamonds represent KOIs whose nature is ambiguous. Transiting giant planets previously published, mostly from ground-based surveys, are shown as triangles. The incident flux is constructed from  $R_*$ ,  $T_{\text{eff}}$ , and  $a$ . From Demory & Seager (2011, Figure 1), by permission of IOP Publishing/AAS.

some  $70M_{\oplus}$  (2/3 of its total) in heavy elements, assumed to be in a core, as inferred for Saturn and Jupiter (Burrows et al., 2007a). Another example, also assumed to be heavy-element rich, is HAT-P-3 b (Torres et al., 2007).

**Rocky planet accretion** Simulations have been made of the results of accretion of inwardly-migrating embryos and rocky planets ( $M_p = 1 - 20M_{\oplus}$ ) by (already-existing) close-in hot Jupiters, finding high collision rates (Ketchum et al., 2011a; Anderson & Adams, 2012; Liu et al., 2015e). Anderson & Adams (2012) calculated the trajectories of incoming rocky planets subjected to gravitational, frictional, and tidal forces. These collisions always increase the metallicity of the Jovian planets. If the incoming rocky bodies survive tidal destruction and reach the central regions, they provide a means of producing large planetary cores. Both the added metallicity and larger cores act to decrease the radii of the gas giants at fixed mass, while collisional energy provides the Jovian planets with an additional heat source, resulting in long-term effects if the colliding body deposits significant energy deep in the interior in regions of high opacity. Both hot Jupiters and newly-formed gas giants have inflated radii large enough to allow incoming rocky planets to survive tidal disruption, enhance the central core mass, and deposit significant energy, while denser giant planets with the mass and radius of Jupiter are expected to tidally destroy incoming rocky bodies.

Liu et al. (2015e) found that during oblique and moderately energetic collisions, the merger products retain a higher fraction of the colliders' cores than their envelopes, depositing considerable spin angular momentum to the gas giants, desynchronising their spins from

their orbital mean motion, and yielding an oblateness that can be used to infer the impact history. Subsequent dissipation of stellar tides inside the planet envelope can lead to runaway inflation and potentially a substantial loss of gas through Roche lobe overflow. The impact of super-Earths on parabolic orbits can also enlarge gas giant envelopes, elevating their tidal dissipation rate over  $\sim 100$  Myr time scale. The fact that giant impacts occur stochastically with a range of impactor sizes and energies, provides another way in which their diverse outcomes may account for the dispersion in the mass–radius relationship of hot Jupiters.

### 6.28.5 Companion planets

Hot Jupiters tend not to be found in multi-planet systems. Close-orbiting companions are rare, although more distant low-mass companions (the ‘cold friends’ of hot Jupiters) may be more common (Latham et al., 2011; Knutson et al., 2014c). This is believed to result from their dynamical evolution from their original birthplace to their current orbits. Mechanisms such as inward migration or Lidov–Kozai oscillations may disrupt previous co-orbiting planets in the system, although others may survive (Fogg & Nelson, 2007b,a). Alternatively, chains of (undetectable, low-mass, exterior) terrestrial planets may eventually drive the hot Jupiter onto the central star (Ogihara et al., 2013). Despite a possibly short lifetime, an inner companion may, before its demise, have promoted damping of a warm Jupiter’s eccentricity and enhanced its internal heating (Van Laerhoven & Greenberg, 2013). N-body simulations of terrestrial planet formation under the influence of a hot Jupiter have been described by Ogihara et al. (2014).

Constraints on companion planets come from radial velocities (for both radial velocity and transit discoveries), transit light curves, or transit timing variations. Companion statistics also depend on the definition adopted for the ‘hot Jupiter’. Specific long-term monitoring programs include the CORALIE survey of WASP hot Jupiters (Neveu et al., 2013), and the Keck-HIRES sample of 51 close-in gas giant planets (Knutson et al., 2014c).

Of hot Jupiters (with  $P < 10$  d and  $M_p > 1M_J$ ) discovered from radial velocity surveys, three are in multi-planet systems (HIP 14810, HD 217107, and Pr 211). Qatar-2 may have a companion (Bryan et al., 2012).

For hot Jupiters with  $M_p \lesssim 1M_J$ , radial velocity studies again find some, but still rather rare instances of non-transiting planets on wide orbits, including  $\nu$  And b (Endl et al., 2014), HAT-P-13 (Bakos et al., 2009b; Szabó et al., 2010), and HAT-P-17 (Howard et al., 2012a).

Of the 150 transiting hot Jupiters (with  $P < 10$  d and  $M_p > 1M_J$ ), some 8 occur in multi-planet systems (Kepler-24, Kepler-28, Kepler-32, Kepler-52, Kepler-57, Kepler-424, WASP-8, and WASP-47), albeit with multiplicities of up to 4–5. WASP-8 b is an example of a close-in hot Jupiter (Queloz et al., 2010) with a more distant companion discovered from radial velocity measures (Knutson et al., 2014c).

WASP-47 b is a transiting hot Jupiter in a 4-d orbit (Helier et al., 2012), with three companions: WASP-47 c, a  $1.6M_J$

planet in a 580-d orbit discovered from radial velocities (Neveu-VanMalle et al., 2016), and two further low-mass companions discovered from Kepler transit photometry, one in a slightly longer 9-d orbit, and an inner in a 0.8-d orbit (Becker et al., 2015). That the additional planets are co-planar with the hot Jupiter and that the planets are unstable with  $e \geq 0.05$  implies that the WASP-47 planets either migrated in a disk or some damping near the end of migration brought them into their present compact architecture (Becker et al., 2015).

Kepler-424 b is a rare example of a 2-planet hot Jupiter system, with a hot Jupiter in a 3.3-d orbit, accompanied by a more massive outer non-transiting companion in an eccentric ( $e = 0.3$ ) 223-d orbit, again discovered from radial velocity measurements (Endl et al., 2014).

Searches for companions from transit timing variations (§6.20) of known hot Jupiters have generally not been successful (Steffen et al., 2012c,b; Maciejewski et al., 2013a), as confirmed by other similar searches (e.g. Ford et al., 2012a; Steffen et al., 2012a; Mazeh et al., 2013; Szabó et al., 2013; Batalha et al., 2013). These results imply an absence of nearby planets in most of these systems. For longer-period and typically more eccentric ‘warm Jupiters’, companions are more common, e.g., Kepler-419 (Dawson et al., 2012, 2014; Dawson & Chiang, 2014; Dong et al., 2014a).

In summary, results from Kepler confirm that hot Jupiters are predominantly isolated in terms of any *nearby* companions, while extended radial velocity monitoring suggests that as many as  $50 \pm 10\%$  have an outer more distant companion with  $1M_J < M_p < 13M_J$  (Knutson et al., 2014c).

**Hot Jupiters and warm Jupiters** Huang et al. (2016) found a clear distinction in the prevalence of sub-Jovian companions between systems that contain hot Jupiters ( $P < 10$  d) and those that host warm Jupiters ( $P = 10 - 200$  d). Hot Jupiters, with the singular exception of WASP-47 b, have no detectable inner or outer planetary companions (with  $P < 50$  d and  $R_p > 2R_\oplus$ , or  $R_p > 2R_\oplus$  for inner companions). In contrast, half of the warm Jupiters are closely flanked by small companions.

Amongst various formation mechanisms proposed for warm Jupiters (§10.10.6), Huang et al. (2016) suggest that warm Jupiters are formed *in situ*, and that WASP-47 b, alone amongst hot Jupiters in having a nearby companion, could be on the tail of the *in situ* warm Jupiters into the hot Jupiter region.

**Expected contributions from Gaia** Gaia should place further constraints on the incidence of outer companions. For example, the astrometric signature (§3.1) of HAT-P-17 c is expected to be  $\alpha \sim 240 \mu\text{as}$ , which should be easily measured (Perryman et al., 2014a). HAT-P-13 c, with  $\alpha \sim 57 \mu\text{as}$ , is probably also above its detection threshold. With  $P \sim 1.2$  yr, several orbits will be sampled, and the mutual inclination determined. Such constraints may also yield the tidal dissipation factor of the inner planet (Batygin et al., 2009a; Mardling, 2010). HAT-P-13 may have a third companion, inferred from an acceleration in the systemic velocity,  $\dot{\gamma} \sim 17.5 \text{ m s}^{-1}$ , and consistent with a massive companion of  $\sim 10M_J$  (Winn et al., 2010b). Gaia should also be able to constrain its mass if its period is sufficiently short.

### 6.28.6 Stellar companions

If Lidov–Kozai oscillations are responsible for at least some of the close-in hot Jupiters (§10.10.6), the host stars should be accompanied by a hierarchical stellar binary component acting as the distant perturber. Various

radial velocity, spectroscopic, and imaging searches for stellar companions of hot Jupiter hosts have been made (Knutson et al., 2014c; Ngo et al., 2015; Piskorz et al., 2015; Wang et al., 2015b; Ngo et al., 2016).

In a 3-yr imaging survey with Keck–NIRC2, Ngo et al. (2015) observed 50 candidate systems, 27 showing some signature of multi-body interaction (misaligned or eccentric orbits), and the remaining ‘control sample’ of 23 having well-aligned and circular orbits. They found 19 stellar companions around 17 stars, with stellar companions in roughly 50% of the cases, and no correlation between misaligned/eccentric hot Jupiter systems and the incidence of stellar companions. Combining this result with a previous radial velocity survey, they estimated that  $72 \pm 16\%$  of hot Jupiters are part of multi-planet and/or multi-star systems.

From their adaptive optics imaging survey, Wang et al. (2015b) found a stellar multiplicity rate for planet host stars of  $0_{-0}^{+5}\%$  within 20 au, compared with a stellar multiplicity rate of  $18 \pm 2\%$  for field stars in the solar neighbourhood. The stellar multiplicity rate for planet host stars rises to  $34 \pm 8\%$  for separations between 20–200 au, higher than the control sample of  $12 \pm 2\%$ . Beyond 200 au, stellar multiplicity rates are comparable between planet host stars and field stars.

### 6.28.7 Satellites

Stability and survival analyses suggest that around stars of  $M_\star > 0.15M_\odot$ , satellites are only stable over  $\sim 5$  Gyr for planetary orbits with  $a \geq 0.6$  au (Ward & Reid, 1973; Barnes & O’Brien, 2002; Cassidy et al., 2009). Within this radius, stellar tides are effective in removing satellites, suggesting that hot Jupiters within  $\sim 0.1$  au are unlikely to be accompanied by satellites. Limits on transit time variations appear to be consistent with this conclusion.

### 6.28.8 Stellar activity and planet surface gravity

The suggestion that stellar activity can be enhanced by the presence of exoplanets (see also §8.10.2 and §8.10.4) has been variously considered (e.g. Saar & Cuntz, 2001; Shkolnik et al., 2008; Poppenhaeger et al., 2011; Poppenhaeger & Wolk, 2014), and may be associated with exoplanet evaporation and evolution (e.g. Lecavelier des Etangs et al., 2010; Boué et al., 2012a).

Knutson et al. (2010) demonstrated a correlation between the emission spectra of transiting planets and their host star chromospheric activity levels, represented by the Ca II H and K emission line strengths: planets with spectra consistent with non-inverted temperature models tend to be found around high-activity stars, while planets with temperature inversions are found around low-activity stars (Figure 6.109).

Based on their catalogue of  $\log R'_{\text{HK}}$  for 39 transiting planets (§2.4.5), Hartman (2010) also demonstrated

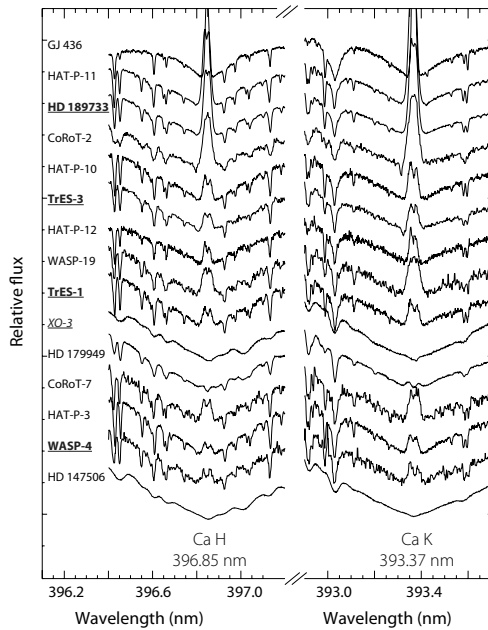


Figure 6.109: Ca II H and K lines for a subset of the transiting planet host stars observed with Keck-HIRES, plotted in order of increasing  $S_{\text{HK}}$ . Active stars (towards the top) have significant emission in the line cores (high  $S_{\text{HK}}$ ). Star names (at left) are shown in underlined italic (here XO-3 only) for planets with temperature inversions, in underlined bold for those without temperature inversions, and in normal font if there was insufficient data for characterisation. From Knutson et al. (2010, Figure 1), by permission of IOP Publishing/AAS.

a significant correlation between the surface gravity of hot Jupiters,  $\log g_p$ , and the activity levels of their host stars: high surface gravity planets tend to be found around high-activity stars. Here,  $g$  comes directly from the spectroscopic orbit and transit light curve, without constraints from stellar or atmospheric models (e.g. Southworth et al., 2007). With a roughly three times larger data set, Figueira et al. (2014b) confirmed the correlation, albeit at a slightly lower confidence level.

Lanza (2014) has attributed the correlation to absorption by circumstellar matter originating from planetary evaporation, providing a theoretical relation (based on an enlarged sample of 54 systems) between the chromospheric emission as measured in the core of the Ca II H and K lines and the planet gravity (Figure 6.110). Planets with a lower gravity have a greater mass-loss rate, which leads to a higher column density of circumstellar absorption, in turn explaining the lower level of chromospheric emission observed in their host stars. Further models have supported the hypothesis (Fossati et al., 2015b).

A consequence of this hypothesis is that chromospheric emission measures cannot immediately be taken as a proxy for the photospheric activity level of

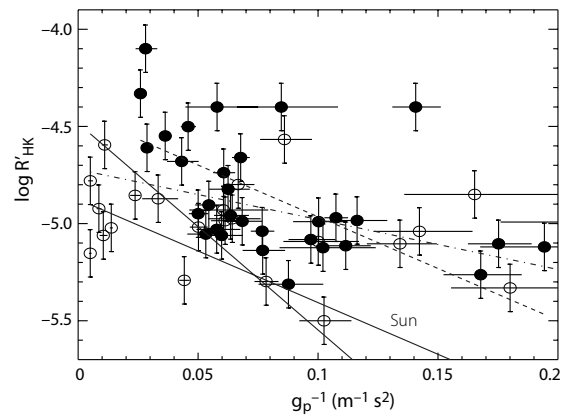


Figure 6.110: Chromospheric emission index  $R'_{\text{HK}}$  versus the inverse of the surface planetary gravity  $g$  for a sample of close-in planets. The dot-dashed line is a linear regression for all 54 planets. The dashed line is for the 31 objects (filled circles) with  $M_p > 0.1M_J$ ,  $a < 0.1 \text{ au}$  and  $4200 < T_{\text{eff}} < 6200 \text{ K}$  (omitted points shown as open circles). Solid lines are theoretical relations (Lanza, 2014, eqn 6) for the Sun (lower slope) and for a star with twice solar chromospheric and  $F_{\text{EUV}}$  fluxes. From Lanza (2014, Figure 2), reproduced with permission © ESO.

a planet-hosting star. The intrinsic activity can be significantly higher than derived from  $R'_{\text{HK}}$ , and this can affect the estimate of the radial-velocity jitter term included when fitting the spectroscopic orbit of a transiting planet. Similarly, age estimates based on the level of chromospheric emission (e.g. Mamajek & Hillenbrand, 2008) would lead to systematically older values than the true ages for stars with low-gravity planets.

### 6.28.9 Other properties

Other studies of hot Jupiters include tidal circularisation (§10.11.3), tidal spin-up (§10.11.8), tidal disruption (§6.14.21), spin-orbit misalignments determined by the Rossiter-McLaughlin effect (§6.18) and others, mass-loss by evaporation (§11.4.5 and §8.10.4), magnetically-controlled (mass-loss) outflows (Adams, 2011; Cohen & Glocer, 2012; Khodachenko et al., 2012; Tanaka et al., 2014), along with other effects of magnetic interaction (star-planet interaction) with their host stars (§8.3.5).

Other studies include an unsuccessful search for resonant disks (exozodiacal clouds) in the Kepler data of hot Jupiter candidates (Stark et al., 2013a), searches for host star variability (Ruban & Arkharov, 2012), revealing microvariability in  $\tau$  Boo with amplitude 0.02 mag at the planet's orbital period, and at a similar amplitude for 51 Peg but at three times the planet's orbital period, and prospects for direct imaging of tidally-powered candidates (Dong et al., 2013a).

**Safronov number** The *Safronov number* is defined in terms of the escape velocity from the surface of the planet,  $V_{\text{esc}}^2 = 2GM_p/R_p$ , and the orbital velocity of the

planet about its host star,  $V_{\text{orb}}^2 = GM_{\star}^2 / a(M_{\star} + M_{\text{p}})$ , as

$$\Theta = \frac{1}{2} \left( \frac{V_{\text{esc}}}{V_{\text{orb}}} \right)^2 = \left( \frac{a}{R_{\text{p}}} \right) \left( \frac{M_{\text{p}}}{M_{\star}} \right). \quad (6.166)$$

It provides a measure of the planet's ability to gravitationally scatter other bodies (Safronov, 1972).

Identification of two classes of hot Jupiter based on  $\Theta$  as a function of equilibrium temperature,  $T_{\text{eq}}$ , was identified by Hansen & Barman (2007) and confirmed by Torres et al. (2008) but subsequently considered less compelling (Southworth, 2009; Fressin et al., 2009).

## 6.29 Host stars

More general considerations of exoplanet host stars are given in Chapter 8, including an overview of the various diagnostic and measurement techniques, such as the determination of metallicity, age, rotation, and inferences from asteroseismology.

Of more than 180 000 stars observed by Kepler, only a small fraction have been observed spectroscopically, and the majority have only photometrically-determined properties (e.g. Brown et al., 2011b; Huber et al., 2014).

Nevertheless, Kepler time series photometry provides its own specific constraints on certain fundamental stellar parameters, with estimates of  $\rho_{\star}$  from asteroseismology and ‘flicker’ providing key inputs to the probing technique of asterodensity profiling (§6.13.11).

Asteroseismology results from Kepler are considered separately in Section 6.29.7.

**Compilations of host star properties** Derived from various sources and methodologies, many primary host star characteristics are tabulated in the major online compilations, notably the NASA Exoplanet Archive and the Extrasolar Planets Encyclopaedia (Table 1.4). Some of the larger compilations of Kepler host star properties are summarised hereafter (see also box, page 176).

Pinsonneault et al. (2012) provided a revised temperature scale for the Kepler Input Catalogue, based on SDSS *griz* filters tied to the fundamental temperature scale. Typical errors, mostly from uncertainties in extinction, are of order 100 K.

Huber et al. (2014) presented revised properties for 196 468 Kepler stars, based on a compilation of literature values for  $T_{\text{eff}}$ ,  $\log g$ , and [Fe/H] (variously derived from photometry, spectroscopy, asteroseismology, and transits), which were then homogeneously fitted to a grid of Dartmouth stellar isochrones. Typical uncertainties in  $R_{\star}$  and  $M_{\star}$  are 40% and 20%, respectively, for stars with photometric constraints only, and 5–15% and 10% when based on spectroscopy and/or asteroseismology. A further revision for 197 096 Q1–Q17 targets was used for the final transit search DR25 (Mathur et al., 2017).

Under favourable circumstances, dynamical masses may be obtained for the host stars in close binary systems, as considered for WASP–12 BC and HAT–P–8 BC (Bechter et al., 2014).

### 6.29.1 Stellar radii

The general method for estimating radii and other parameters of transiting-planet host stars, and hence the radii of the planets themselves, is again to match theoretical models to observations of the stellar mean density  $\rho_{\star}$ , the effective temperature  $T_{\text{eff}}$ , and the composition parameter [Z].

Comparing theoretical (Yonsei–Yale) stellar evolution models with stars with well-determined masses and radii (eclipsing binaries, and asteroseismically modeled stars) Brown (2010) identified a systematic effect for rapidly rotating stars, leading to a mass-dependent underestimate of stellar radii by up to 4% at  $0.4M_{\odot}$  (with relative errors in  $M_{\star}$  being three times larger). The asteroseismic sample suggests that systematic errors are small for slowly rotating, inactive stars, yielding radii that are accurate to about 2% for most stars.

### 6.29.2 Stellar densities

Several hundred Kepler stars have estimates of  $\rho_{\star}$ , either from the transit light curve (§6.13.7), from asteroseismology (§6.29.7), from the comparison of high-resolution spectroscopic observations with stellar evolutionary isochrones (viz., a catalogue of library spectra with various  $T_{\text{eff}}$ , [M/H] and  $\log g$ ), or via the photometric ‘flicker’ correlation.

**Flicker** Variability over a canonical 8-hour time scale, referred to as *flicker*, is accurately determinable for very large numbers of Kepler stars because of the high accuracy, high cadence, and long-duration photometry, and has been developed as a particular stellar diagnostic.

Basri et al. (2011) quantified high-frequency noise in the Kepler photometry using a 4-point smoothing. Bastien et al. (2013) showed it to be an empirical proxy for the stellar surface gravity,  $g_{\star}$ , and found that a 16-point (8-h) smoothing yielded the cleanest correlation with the asteroseismically measured  $\log g_{\star}$  (Figure 6.111).

Physically attributed to stellar surface granulation (Mathur et al., 2011; Cranmer et al., 2014), the trend reproduces  $\log g_{\star}$  to within  $\sim 0.10$  dex for FGK dwarfs and giants down to  $14 M_{\odot}$  (see also Figueira et al., 2016a).

Kipping et al. (2014a) measured the high-frequency stellar noise ( $F_8$ ) in the long-cadence (30 min) Kepler light curves from the rms difference between the light curve and a box-car smoothed version, and found that  $\rho_{\star}$  could be estimated, to  $\sim 14$  mag and to within about 30%, from the regression

$$\log_{10} \left( \frac{\rho_{\star}}{\text{kg m}^{-3}} \right) = \alpha + \beta \log_{10} \left( \frac{F_8}{\text{ppm}} \right), \quad (6.167)$$

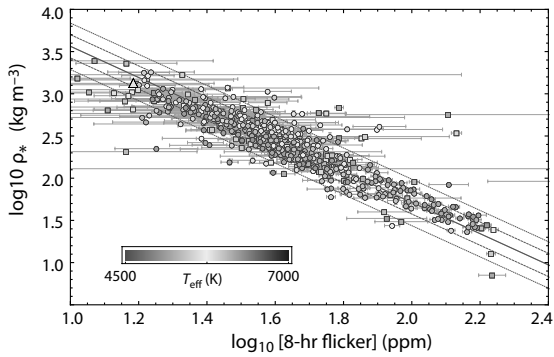


Figure 6.111: Empirical relation between stellar density,  $\rho_*$ , and the 8-h Kepler photometric ‘flicker’,  $F_8$ . The best-fit linear relation is shown by the solid centre line. Lateral dashed and dotted lines are the  $1\sigma$  and  $2\sigma$  confidence regions. Points are grey-scale coded by the effective temperature (colour in the original figure), and the Sun is marked with a triangle. Squares are unreliable points not used in the fit. From Kipping et al. (2014a, Figure 1), by permission of IOP Publishing/AAS.

with the values  $\alpha = 5.413$  and  $\beta = -1.850$ .

Applying a flicker measurement-based recalibration of 289 bright Kepler stars, Bastien et al. (2014a) showed that for the brightest host stars, Malmquist bias contaminates the stellar sample with evolved stars: nearly 50% of the bright planet-host stars are subgiants. As a result,  $R_*$ , and hence  $R_p$ , are on average 20–30% larger than previous measurements had suggested.

Flicker-derived densities should also be of benefit for the transiting missions, TESS and PLATO (Kipping et al., 2014a). The smaller 0.12-m aperture for TESS will lead to higher photon noise compared with Kepler. The useful (flicker) magnitude limit would rise to  $\sim 11.5$ , yielding some  $10^5$  targets amenable to a flicker-based determination of  $\rho_*$ , with some  $5 \times 10^3$  suitable asteroseismology targets out of a  $5 \times 10^5$  target total.

### 6.29.3 Metallicity dependence

The dependence of planet occurrence on metallicity is considered more generally in Section 8.4.2.

In brief, for stars in the solar neighbourhood, the mass fraction of metals ranges from a few percent down to  $\sim 0.01\%$ . Radial velocity surveys have demonstrated that the fraction of high-metallicity stars hosting giant planets is much larger than for low-metallicity stars (e.g. Santos et al., 2001a, 2004c; Fischer & Valenti, 2005; Sousa et al., 2011b). Assuming that the initial protostellar disk has the same composition as its host star, and that the heavier elements are the raw material from which most of the mass in a typical planet must be assembled, it is then natural to expect that planet formation should be more successful around stars of higher metallicity.

Ground-based surveys suggest that this correlation is weaker for Neptune-sized planets (Sousa et al., 2011b);

Udry et al., 2006; Sousa et al., 2008; Ghezzi et al., 2010c), with the relationship for the yet lower-mass terrestrial-sized exoplanets poorly defined.

Schlaufman & Laughlin (2011) used the  $J - H$  versus  $g - r$  colour–colour diagram to demonstrate that Kepler exoplanet host stars are also preferentially metal rich. They also found a correlation between metallicity and the occurrence of small-radius planets around late K dwarfs, findings later attributed to mis-classification of giants as dwarfs (Mann et al., 2012, 2013b).

Buchhave et al. (2012) used Kepler results for 152 planet hosts to confirm occurrence–metallicity correlation for large planets. They found that planets with  $R_p \lesssim 4R_\oplus$  have a wide range of metallicity, with a median close to solar, and concluded that there was no planet–metallicity correlation for planets smaller than  $R_p \lesssim 4R_\oplus$ . Everett et al. (2013) reached similar conclusions from a spectral analysis of 220 faint ( $K_p > 14$  mag) Kepler planet host stars.

Buchhave et al. (2014) expanded their metallicity measures to 406 Kepler planet host stars, finding average metallicities for gas giant planets and gas dwarf planets that are above solar ( $0.18 \pm 0.02$  dex and  $0.05 \pm 0.01$  dex respectively), while the average metallicity for terrestrial planets is consistent with solar, at  $-0.02 \pm 0.02$  dex.

Wang & Fischer (2015) used a well-characterised subset from Buchhave et al. (2014) to suggest a more universal planet–metallicity correlation: not only gas-giants ( $3.9R_\oplus < R_p \leq 22R_\oplus$ ) but also gas-dwarf ( $1.7R_\oplus < R_p \leq 3.9R_\oplus$ ) and terrestrial planets ( $R_p \leq 1.7R_\oplus$ ) occur more frequently around metal-rich stars, with occurrences 9.3, 2.0, and 1.7 times higher for metal-rich stars than for metal-poor stars, respectively.

### 6.29.4 Mass dependence

Several studies have inferred the occurrence rates of planets from the entire Kepler sample of planetary candidates, which mainly contains planets around main sequence stars with spectral types F, G, and K (e.g. Howard et al., 2012b; Fressin et al., 2013; Petigura et al., 2013b). In general, planet occurrence increases with  $a$  up to  $P \sim 10$  d (Howard et al., 2012b), and becomes flat further out (Yudin, 2011b; Catanzarite & Shao, 2011b; Traub, 2012; Dong & Zhu, 2013; Silburt et al., 2015).

Particular attention has also been given to the cooler, lower-mass M dwarfs, where planets smaller and closer to the habitable zone can be detected (Dressing & Charbonneau, 2013; Morton & Swift, 2014).

That Kepler planets are, by virtue of the transit geometry, located relatively close to the star, means that observed distributions may also contain imprints of star–planet interactions, either during formation in a protoplanetary disk, or afterwards through tidal interactions. These effects may shape the planet distribution in different ways according to stellar mass (box, page 309).



**Stellar mass dependencies:** Various mechanisms may control planet occurrence as a function of stellar mass and orbital radius, and in particular over the range  $M_\star \sim 0.3 - 1.5M_\odot$  probed by Kepler (Mulders et al., 2015b).

Their precursor environments, protoplanetary disks, show strong stellar mass dependence on disk mass (Mohanty et al., 2013; Andrews et al., 2013), accretion rate (e.g. Hartmann et al., 2006; Alcalá et al., 2014), inner disk radius (Monnier & Millan-Gabet, 2002; Millan-Gabet et al., 2007), dust evolution (Apai et al., 2005), and disk chemistry (Pascucci et al., 2009). Such scaling laws do not necessarily mean that the first steps of planet formation are stellar-mass dependent (Mulders & Dominik, 2012), although the later stages most likely are (e.g. Raymond et al., 2007b).

For  $M_\star = 1M_\odot$ , Kepler probes a region corresponding to the inner edge of the protoplanetary disk, with the co-rotation radius of the gas at  $\sim 0.05\text{--}0.1$  au, and the dust sublimation radius at  $\sim 0.05$  au for a passive disk (Pinte et al., 2008) and  $\sim 0.1$  au for an actively accreting one (Min et al., 2011). Planet occurrence rates may be reduced inside these radii, either by a lack of solid material for *in situ* formation (Chiang & Laughlin, 2013; Boley et al., 2014) or by trapping migrating planets at or outside the co-rotation or sublimation radius (Lin et al., 1996; Kuchner & Lecar, 2002). For the less massive Kepler stars, these radii were located much closer to the star, even during their bright pre-main sequence stage. Hence a smaller inner disk radius may explain the high occurrence of close-in planets.

The current planetary distribution may be further shaped after disk dissipation. Tides raised on the star may lead to the inspiral of close-in planets on Gyr time scales, as implied by the deficiency of hot-Jupiters within 0.05 au (Jackson et al., 2009). Secular interactions in multi-planet systems may prevent orbit circularisation, or excite their eccentricities (Correia et al., 2012; Greenberg et al., 2013) and lead to tidal destruction of planets from farther out (Lanza & Shkolnik, 2014). Planets with gaseous envelopes may also be partially evaporated (Owen & Wu, 2013).

Boley et al. (2014) have suggested dust sublimation as a likely origin of the innermost planets in multi-planet systems: as solids spiral inward due to aerodynamic drag, they will encounter high temperatures, densities, and pressures. High partial pressures of rock vapour can suppress solid evaporation, and promote collisions between partially molten solids, allowing rapid growth. They suggest that this process should be ubiquitous in planet-forming disks, as evidenced by the abundant class of ‘systems with tightly packed inner planets’ found by Kepler.

Plavchan & Bilinski (2013) confirmed that a scaling law for the location of close-in Kepler planets with stellar mass exists, but of undetermined origin.

Mulders et al. (2015b) derived planetary occurrences around stars of different spectral types (as a proxy for  $M_\star$ ) as a function of  $R_p$  and  $a$ , and identified two trends. First, the occurrence of Earth- to Neptune-sized planets ( $1 - 4R_\oplus$ ) is successively higher toward later spectral types (lower  $M_\star$ ) at all orbital periods probed by Kepler, with planets around M stars occurring twice as frequently as around G stars, and three times as frequently as around F stars.

Second, a fall-off in planet occurrence is evident at all spectral types for  $P < 10$  d, with a plateau further out. The location of the fall-off scales with  $a$  as  $M_\star^{1/3}$ . By comparing different mechanisms of planet formation, trapping, and destruction, they found that this scaling best matches the location of the pre-main-sequence co-rotation radius, indicating efficient trapping of migrating planets or planetary building blocks close to the star.

### 6.29.5 Rotation and gyrochronology

Stellar rotation periods have been estimated for large numbers of Kepler stars (planet hosts, as well as field stars) from the rotational modulation of surface star spots. These rotation periods can then be used to estimate stellar ages based on *gyrochronology*, which exploits a star’s gradual angular momentum loss over time (see Section 8.2.6). Ages accurate to some  $\sim 15\%$  are claimed (e.g. Meibom et al., 2011a; Nielsen et al., 2013b; Reinhold & Reiners, 2013; McQuillan et al., 2013a; Reinhold et al., 2013; Reinhold & Gizon, 2015; Aigrain et al., 2015b; Angus et al., 2015).

McQuillan et al. (2013a) analysed 10 months of Kepler data to detect rotation periods in 1570 stars, with periods ranging from 0.37–69.7 d, and amplitudes in the range 1.0–140.8 mmag. They identified a bimodal rotation period distribution, with peaks at 19 and 33 d, suggesting two distinct waves of star formation, a hypothesis supported by the fact that slower rotators tend to have larger proper motions. The two peaks of the rotation period distribution form two distinct sequences in period–temperature space, with  $P$  decreasing with increasing  $T_{\text{eff}}$ .

McQuillan et al. (2013b) analysed 1919 main sequence exoplanet host stars from the first three years of public Kepler data, deriving robust rotation periods for 737. Comparing the detected stellar periods to the orbital periods of the innermost planet in each system revealed a notable lack of close-in planets around rapid rotators (see below).

Walkowicz & Basri (2013) derived rotation periods, variability measures, and ages for some 950 KOI host stars. They found a wide dispersion in the photometric variability amplitude as a function of rotation, likely indicating differences in the spot distributions. Combining the rotation periods with published spectroscopic measurements of  $v \sin i$ , they derived the stellar inclination to the line-of-sight, and found a number of systems with possible spin–orbit misalignment. They also found several systems with close-in (candidate) planets whose stellar rotation periods are equal to or twice the planetary orbital period, indicative of possible star–planet tidal interactions.

García et al. (2014) reported large-scale calibrations of the age–rotation–activity relation for 540 Kepler stars from asteroseismology.

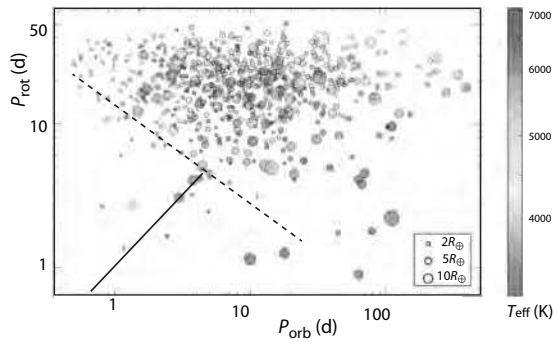


Figure 6.112: Stellar rotation versus orbital period of the inner planet for the 737 KOIs with rotation periods measured by McQuillan et al. (2013b). Point sizes scale as  $R_p^2$ . The dashed line is a fit to the lower envelope of points. The solid line is the 1:1 synchronisation between  $P_{\text{orb}}$  and  $P_{\text{rot}}$ . From McQuillan et al. (2013b, Figure 2), by permission of IOP Publishing/AAS.

McQuillan et al. (2014) used the full 3-yr autocorrelation sample to derive (star spot) rotation periods, in the range 0.2–70 d, for 34 030 Kepler main-sequence stars with  $T_{\text{eff}} < 6500$  K, out of the total of 133 000 main sequence Kepler targets. The resulting period–temperature distribution demonstrates that a period bimodality, first seen by McQuillan et al. (2013a) in the M-dwarf sample, persists to higher masses, becoming less visible above  $0.6M_{\odot}$ . The results are broadly consistent with the existing ground-based rotation-period data, with the upper envelope of the period distribution being broadly consistent with a gyrochronological age of 4.5 Gyr, based on the isochrones of (Barnes, 2007b; Mamajek & Hillenbrand, 2008; Meibom et al., 2009).

Buzasi et al. (2016) compared the rotation periods and photometric activity of 95 KOI planet hosts and 954 solar analogues without detected planets. Their findings included rotation periods averaging roughly 20 d (but with a wide dispersion), and a weak rotation–activity relation for  $P_{\text{rot}} < 12$  d. Their KOI sample is consistently some 0.3 dex more variable than the non-KOIs, ascribed to a selection effect due to low orbital obliquity in the planet-hosting stars with a mean derived obliquity of  $6_{-6}^{+5}\text{°}$ , similar to that of the solar system (§12.1.5).

**Short-period planets around fast rotators** McQuillan et al. (2013b) derived a large sample of 737 stellar rotation periods for KOIs, based on three years of public Kepler data. Comparing the stellar periods to the orbital periods of the innermost planet in each system (Figure 6.112) reveals an absence of close-in planets ( $P_{\text{orb}} \lesssim 2-3$  d) around rapidly rotating stars ( $P_{\text{rot}} \lesssim 5-10$  d). They fitted a line with a slope of  $-0.69$  to the lower edge of the distribution bounded by  $P_{\text{orb}} \leq 10$  d and  $P_{\text{rot}} \geq 3$  d. They also noted several objects below the lower edge that exhibit near-synchronous rotation,  $P_{\text{rot}} \approx P_{\text{orb}}$ .

The sample was extended by McQuillan et al. (2014), and the findings were confirmed by Walkowicz & Basri

(2013), who deduced the rotation periods of  $\sim 950$  KOI hosts using Fourier-based periodograms. They found a significant absence of planets with  $P_{\text{orb}}$  and  $P_{\text{rot}} \lesssim 6$  d, a concentration of planets with  $P_{\text{rot}} \approx P_{\text{orb}}$ , and the presence of a few systems with  $P_{\text{rot}} \approx 2P_{\text{orb}}$ . They noted that all planets along these two loci have radii  $R_p > 6 R_{\oplus}$ .

**Tidal interactions** Teitler & Königl (2014) found that the short-period void can be explained by tidal interaction between close-in planets and their (typically Sun-like) host stars. Over the system lifetimes, the close-in planets spiral inwards, and deposit their orbital angular momenta in the host star’s envelope.

The spin evolution of a star may be affected by the tidally-induced ingestion of close-in planets. Jackson et al. (2009) suggested that the process could account for the observed orbital distribution of close-in planets, and pointed out the dependence of the results on the initial  $P_{\text{orb}}$  distribution as well as on the systems’ age distribution. Pont (2009) emphasised the dependence of the tidal interaction on  $M_p$ . Bolmont et al. (2012) highlighted the implications of such stellar spin-up on the reliability of gyrochronology.

Teitler & Königl (2014) focused on the distribution of low-period KOIs in the  $\log P_{\text{orb}} - \log P_{\text{rot}}$  plane. Broadly, since the angular momentum of a planet of given mass moving on a Keplerian orbit scales as  $P_{\text{orb}}^{1/3}$ , and its in-spiral onset time is  $\propto P_{\text{orb}}^{13/3}$  (Teitler & Königl, 2014, §2), progressively lower values of  $P_{\text{rot}}$  correspond to the tidal ‘ingestion’ of planets with progressively larger values of  $P_{\text{orb}}$ . This results in an inverse correlation between  $P_{\text{rot}}$  and the orbital period of the surviving closest-in planet.

Their model incorporates two physical processes that affect the stellar envelope, and which act to counter the spin-up of planet ingestion. The first is core–envelope coupling, through which the envelope shares its angular momentum with the rest of the star. The second is magnetic braking, the process invoked to account for the apparent rotation–age correlation underlying the gyrochronology age-determination method for solar-type stars (§8.2.6). The braking time is typically  $< 10^9$  yr for  $P_{\text{rot}} < 10$  d, which explains the finding that the systems at the lower edge of the close-in planet distribution are generally among the youngest.

They consider planets on circular orbits in the star’s equatorial plane, and neglect planetary spin, tidal dissipation within the planet, and any planet–planet interactions; the assumption of circular orbits being motivated by the expectation that the time scale for tidal capture is determined by the initial semi-major axis  $a$  rather than by its initial eccentricity (Jackson et al., 2009), and supported by the inference from observations that orbit circularisation may be faster than orbital decay (e.g. Matsumura et al., 2010a).

The star is modeled as an envelope with a moment of inertia  $I_e$  and rotation period  $P_{\text{rot}}$ , and a core with a mo-

ment of inertia  $I_{\text{core}} = I_{\star} - I_{\text{e}}$  and rotation period  $P_{\text{core}}$  (and neglecting the possible changes of  $I_{\text{e}}$  and  $I_{\text{core}}$  with time). The basic evolution equations are

$$\frac{dP_{\text{orb}}}{dt} = -\frac{27\pi}{Q'_{\star}} \frac{M_{\text{p}}}{M_{\star}} \frac{R_{\star}^5}{a^5} \left(1 - \frac{P_{\text{orb}}}{P_{\text{rot}}}\right), \quad (6.168)$$

$$\begin{aligned} \frac{dP_{\text{rot}}}{dt} = & \frac{9\pi}{Q'_{\star}} \frac{M_{\text{p}}}{M_{\star} + M_{\text{p}}} \frac{M_{\text{p}} R_{\star}^2}{I_{\text{e}}} \frac{R_{\star}^3}{a^3} \frac{P_{\text{rot}}^2}{P_{\text{orb}}^2} \left(1 - \frac{P_{\text{orb}}}{P_{\text{rot}}}\right) \\ & - \frac{P_{\text{rot}}^2 N_{\text{mag}}}{2\pi I_{\text{e}}} + \left(1 - \frac{I_{\text{e}}}{I_{\star}}\right) \frac{P_{\text{rot}}}{\tau_{\text{c}}} \left(1 - \frac{P_{\text{rot}}}{P_{\text{core}}}\right), \end{aligned} \quad (6.169)$$

$$\frac{dP_{\text{core}}}{dt} = \frac{I_{\text{e}}}{I_{\star}} \frac{P_{\text{core}}}{\tau_{\text{c}}} \left(1 - \frac{P_{\text{core}}}{P_{\text{rot}}}\right). \quad (6.170)$$

Here,  $N_{\text{mag}}$  is the magnetic braking torque, and  $\tau_{\text{c}}$  is the core–envelope coupling time. The right-hand side of Equation 6.168, and the first term in Equation 6.169, represent the effect of tidal friction in the star on  $P_{\text{orb}}$  and  $P_{\text{rot}}$ , respectively. The second term in Equation 6.169 represents the effect of magnetic braking, and the last term in Equation 6.169 and in Equation 6.170 represent the effect of core–envelope coupling. Magnetic braking and angular momentum transport follows the formulation for solar-type stars (e.g. Denissenkov et al., 2010).

Matsakos & Königl (2015) argued that this type of tidal interaction and planet ingestion can, in principle, account for the alignment exhibited by planets around cool stars irrespective of the planet’s mass or orbital period, the prevalence of misaligned planets around hot stars, the apparent upper bound on the mass of hot Jupiters on retrograde orbits, and the inverse correlation between stellar spin periods and hot-Jupiter masses.

Effects of planet ingestion on star colours and magnitudes have also been analysed by Tognelli et al. (2016).

**Differential stellar rotation** Differential stellar rotation has been measured for many thousands of Kepler target stars, including a number of exoplanet host stars. Measurements have been made principally from the periodicity signatures of multiple co-rotating star spots, but also via light-curve inversion techniques (§8.3.3).

**A stars** Balona (2014) found that a considerable fraction of A stars from Kepler (~19%) have a peculiar feature in the periodogram, comprising a broad peak, attributed to differential rotation in a spotted star, and a sharp peak at slightly higher frequency implying a strictly coherent periodicity. They argued that neither rotation nor pulsation can provide a suitable explanation, and suggested that it could be due to a planet in synchronous orbit around the rapidly rotating, spotted A star, not necessarily in transit.

**Angular momentum** Comparison of a star’s angular momentum with the system’s total angular momentum, i.e., in both star and orbiting planets, provides insight into planet formation processes, in analogy with the ‘angular momentum problem’ of the solar system (§8.3.4).

### 6.29.6 Stellar obliquities

Stellar obliquities, or at least their projections on the sky plane (§8.3.2), have been determined for only a dozen or so Kepler systems. Most of these have been derived through spectroscopic measurements of the Rossiter–McLaughlin effect (§6.18). The fact that obliquities are available for relatively few Kepler systems is due to the general faintness of the host stars compared to the demands of high-resolution spectroscopy.

Obliquities can also be constrained for transiting systems by combining measurements of the star’s rotation period (here, inferred from the flux variation due to star spots), its radius, and the projected rotational velocity, with  $i_{\star} = 90^{\circ}$  suggesting spin–orbit alignment (e.g. Hirano et al., 2012b, 2014; Morton & Winn, 2014).

Almost half of the measured *projected* obliquities exceed  $20^{\circ}$  and 15% exceed  $90^{\circ}$ , with the width of the distribution of true obliquities being even larger (Lissauer et al., 2014a). This result is quite different from the expectation for a model in which the host star and planets form from a single rotating gas disk and thus should have a common spin and orbital axis.

One possibility is that the close-in giant planets arrived on their present orbits via high-eccentricity migration, which excites large obliquities (Fabrycky & Tremaine, 2007). Another possibility is that the stellar spin is misaligned with the axis of the planetary disk, perhaps because of a collision with a giant planet on a highly eccentric orbit, or twisting of the planetary disk by external torques (Tremaine, 1991; Heller, 1993; Batygin, 2012). To complicate the situation further, most of the handful of Kepler planets for which measurements are available, including multi-planet systems, have obliquities near zero (Sanchis-Ojeda et al., 2012; Chaplin & Miglio, 2013; Hirano et al., 2014).

Morton & Winn (2014) used a Bayesian technique for recovering the obliquity distribution, and applied it to a sample of 70 KOIs. They found that the obliquities of stars with only a single detected transiting planet are systematically larger than those with multiple detected transiting planets. This suggests that a substantial fraction of Kepler’s single-transiting systems represent dynamically hotter, less orderly systems than the ‘pancake-flat’ multiple-transiting systems.

For hot Jupiters, results for the high-obliquity system WASP-7 ( $86 \pm 6^{\circ}$ ) conform with the previously-noted pattern, that host stars lacking thick convective envelopes have high obliquities (Albrecht et al., 2012a).

### 6.29.7 Asteroseismology

In addition to its emphasis on exoplanet transits, Kepler includes a significant asteroseismology programme, focused on detailed studies of stellar interiors (see Section 8.6). It is conducted through the Kepler Asteroseismic Science Consortium (KASC), whose 400 members are organised into 13 working groups by variable star type (Kjeldsen et al., 2010). Typical results of their asteroseismic analysis yield an improvement of some orders of magnitude compared to pre-Kepler and CoRoT, with fundamental parameters of giants, subgiants and bright

dwarfs being determined at the percent level. Solar-like oscillators with the best asteroseismic properties are collected in the Kepler dwarfs ‘legacy’ sample (Lund et al., 2017b; Silva Aguirre et al., 2017; Moya et al., 2017; Roxburgh, 2017). A similar ‘Galactic archaeology programme’ is being undertaken with K2 (Stello et al., 2017).

Kepler targets for which asteroseismology oscillation modes have been detected provide two immediate basic parameters: the average large frequency separation between consecutive overtones of the same spherical angular degree,  $\Delta\nu$ , and the frequency of maximum oscillations power,  $\nu_{\max}$ . This latter term is functionally dependent on the surface gravity of the host star,  $g_*$ , and the effective temperature,  $T_{\text{eff}}$  (Brown et al., 1991; Kjeldsen & Bedding, 1995; Chaplin et al., 2008; Belkacem et al., 2011) via

$$(\nu_{\max}/\nu_{\max,\odot}) \approx (g_*/g_\odot)(T_{\text{eff}}/T_{\text{eff},\odot})^{-1/2}, \quad (6.171)$$

where  $\nu_{\max,\odot}$  is Sun’s frequency of maximum oscillations power,  $T_{\text{eff},\odot}$  is the Sun’s effective temperature and  $g_\odot$  is the Sun’s surface gravity. The derived surface gravity is therefore moderately dependent upon some independent measure of  $T_{\text{eff}}$ . The other basic seismic observable,  $\Delta\nu$ , scales with the star’s mean stellar density (Ulrich, 1986) as

$$(\Delta\nu/\Delta\nu_\odot) \approx \sqrt{\rho_*/\rho_\odot}, \quad (6.172)$$

where  $\rho_\odot$  is the Sun’s mean density.

The catalogues of Huber et al. (2013b, 66 stars) and Chaplin et al. (2014, ~500 stars), together include Kepler asteroseismology results, including  $\rho_*$ , for 588 stars.

Amongst the numerous studies of relevance to exoplanet host stars: Kjeldsen et al. (2010) reported that data from the first 7 months of the mission contained 2937 targets observed at a 1-min cadence for periods between 10 d and 7 months.

Huber et al. (2013b) determined fundamental properties for 66 Kepler planet-candidate hosts, with typical uncertainties of 3% in radius and 7% in mass. They included new asteroseismic solutions for four confirmed planet hosts (Kepler-4, Kepler-14, Kepler-23 and Kepler-25), and brought the number of Kepler host stars with asteroseismic solutions at the time to 77.

**Example modeling** Three example results are given here. Others can be found from Appendix D.

*Kepler-10:* Fogtman-Schulz et al. (2014) used 29 months of Kepler data to confirm that Kepler-10 is the oldest known rocky-planet-harboring system at  $10.41 \pm 1.36$  Gyr, and yielding the radius of Kepler-10 b with an uncertainty of  $\pm 125$  km.

*Kepler-93:* Ballard et al. (2014) showed that  $\rho_* = 1.652 \pm 0.006 \text{ Mg m}^{-3}$  from asteroseismology is consistent with the less precise value from transit modeling

Table 6.3: The Kepler-410A system from asteroseismology modeling (Van Eylen et al., 2014, Table 3). Stellar parameters are from the best-fit model without overshoot (the differences between models with overshoot are taken as a measure of the systematic modeling error, and the difference added in quadrature to the grid optimisation uncertainties). Planet values are from transit modeling combined with asteroseismic results.

Stellar parameters	Kepler-410A
mass, $M_*$ ( $M_\odot$ )	$1.214 \pm 0.033$
radius, $R_*$ ( $R_\odot$ )	$1.352 \pm 0.010$
surface gravity, $\log g$ (cgs)	$4.261 \pm 0.007$
mean density, $\rho$ ( $\text{Mg m}^{-3}$ )	$0.693 \pm 0.009$
age (Gyr)	$2.76 \pm 0.54$
luminosity, $L_*$ ( $L_\odot$ )	$2.72 \pm 0.18$
distance, $d$ (pc)	$132 \pm 6.9$
inclination, $i_*$ ( $^\circ$ )	$82.5^{+7.5}_{-2.5}$
rotation period, $P_{\text{rot}}$ (d)	$5.25 \pm 0.16$
Model parameters	Kepler-410A b
rotational splitting, $\nu_s$ ( $\mu\text{Hz}$ )	$2.206^{+0.067}_{-0.065}$
rotation speed, $\nu \sin i_*$ ( $\text{km s}^{-1}$ )	$12.9 \pm 0.6$
$(V_1/V_0)^2$	$1.796^{+0.090}_{-0.085}$
$(V_2/V_0)^2$	$0.861^{+0.073}_{-0.068}$
Planet parameters	Kepler-410A b
orbital period, $P$ (d)	$17.833648 \pm 0.000054$
radius, $R_p$ ( $R_\oplus$ )	$2.838 \pm 0.054$
semi-major axis, $a$ (au)	$0.1226 \pm 0.0047$
eccentricity, $e$	$0.17^{+0.07}_{-0.06}$
inclination, $i_p$ ( $^\circ$ )	$87.72^{+0.13}_{-0.15}$
Model parameters	Kepler-410A b
$a/R_*$	$19.50^{+0.68}_{-0.77}$
$R_p/R_*$	$0.01923^{+0.00034}_{-0.00033}$
linear limb darkening	$0.57^{+0.22}_{-0.28}$
quadratic limb darkening	$-0.04^{+0.26}_{-0.22}$

( $1.72^{+0.02}_{-0.28} \text{ Mg m}^{-3}$ ).  $R_*$  from asteroseismology, combined with  $R_p/R_*$  from the transit depth, yields  $R_p = 1.481 \pm 0.019 R_\oplus$ , corresponding to an uncertainty of  $\pm 120$  km. Together with  $M_p = 3.8 \pm 1.5 M_\oplus$ , this yields a (rocky) density of  $6.3 \pm 2.6 \text{ Mg m}^{-3}$ .

*Kepler-410:* Van Eylen et al. (2014) derived  $M_*$ ,  $R_*$ , and age. The star’s rotation period and inclination can also be determined, from rotationally-induced splitting (Figure 6.113). Planet parameters, and a detailed characterisation of the star-planet system, follow from the modeled transit light curve (Table 6.3).

**Asteroseismic determination of obliquities** The stellar rotation axis from asteroseismology can be combined with the inclination of the planetary orbit plane to yield the host star’s obliquity directly (§8.3.2).

For example, Kepler-50 and Kepler-65 are systems with multiple transiting small planets, and both stars show rich spectra of solar-like oscillations. Chaplin et al. (2013) established that each host has its rotation axis

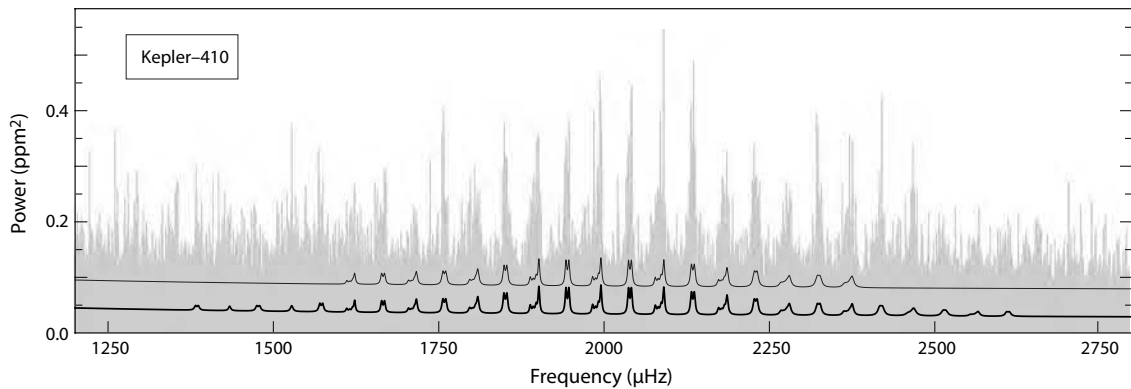


Figure 6.113: Asteroseismic power spectrum of Kepler-410 (grey background). The heavier curve gives the model including all modes in the range 1370–2630  $\mu\text{Hz}$ . The lighter curve (displaced upwards for clarity) excludes the five outermost modes at each end of the frequency scale. The difference between the two fits provides estimates of the stellar inclination and the frequency splitting. From Van Eylen et al. (2014, Figure 1), by permission of IOP Publishing/AAS.

nearly perpendicular to the line-of-sight, implying low obliquities, and they used statistical arguments to show that co-planar orbits are favoured. For Kepler-56, similar analysis favours a co-planar system but with a high obliquity,  $\psi \sim 45^\circ$  (Huber et al., 2013a).

### 6.29.8 Stellar binarity/multiplicity

Imaging searches to improve understanding of the stellar binarity or multiplicity of Kepler host stars is described in Section 7.9.3.

## 6.30 Multiple planet systems

### 6.30.1 Overview of Kepler results

Kepler-9 was the first star for which multiple transiting planets were observed (Holman et al., 2010). Several hundred transiting multi-planet systems have since been discovered from the Kepler data.

Multiple systems are expected to have a very low false-positive rate,  $\lesssim 1\%$ . This is essentially because, while background binary-star eclipses may mimic the light curve from a single transiting planet, they are unlikely to imitate two or more (Lissauer et al., 2012b, 2014b). In addition, correlated transit timing variations, observed in a number of multi-planet systems, provide unequivocal confirmation that the associated planets are themselves interacting gravitationally.

The analysis of multi-planet systems is providing important diagnostics of planets and planet formation for a number of reasons.

The gravitational interactions that occur between planets in the same system, and which frequently lead to significant variations in transit times (Section 6.20), allow, in favourable cases, determination of the masses and orbital properties of one or more of the planets.

The statistics of single and multi-planet systems provide significant constraints on orbital co-planarity, in turn constraining the mechanisms operational during their formation and evolution (Section 6.30.5).

**Statistics of single and multiple systems** About one-third of the 1200 transiting planet candidates detected in the first four months of Kepler data are members of multiple (candidate) systems, and 17% of the total number of systems (170 out of 997 systems). Specifically, there were 827 systems with only one candidate transiting planet, 115 target stars with two, 45 with three, 8 with four, and 1 each with five and six (a total of 170 multiple systems with 408 candidates).

Analysis of the first 16 months of data added 1108 new candidates, and brought the total number of transiting candidates to over 2300 (Batalha et al., 2013). The resulting sample contained 1409 single planet systems, and 365 multiple systems with a total of 899 planets (Fabrycky et al., 2014): 243 stars with two candidate transiting planets, 85 3-planet systems, 28 4-planet systems, 8 5-planet systems, and one 6-planet system.

Single and multiple systems are both dominated by planets smaller than Neptune ( $R_p \lesssim 3 - 4R_\oplus$ );  $69_{-3}^{+2}\%$  for singles and  $86_{-5}^{+2}\%$  for multiples. The fact that systems with multiple transiting planets are less likely to include a transiting *giant* planet, suggests that close-in giant planets tend to disrupt the orbital inclinations of small planets in flat systems, or maybe even prevent the formation of such systems in the first place.

A montage of candidate systems with three or more planets, from the first 16 months of data, and ordered by the innermost orbital period, is given in Fabrycky et al. (2014, their figure 1). A compilation of all transiting systems with multiplicity 3 or higher as of end 2017, dominated by Kepler systems, is shown in Figure 6.114.

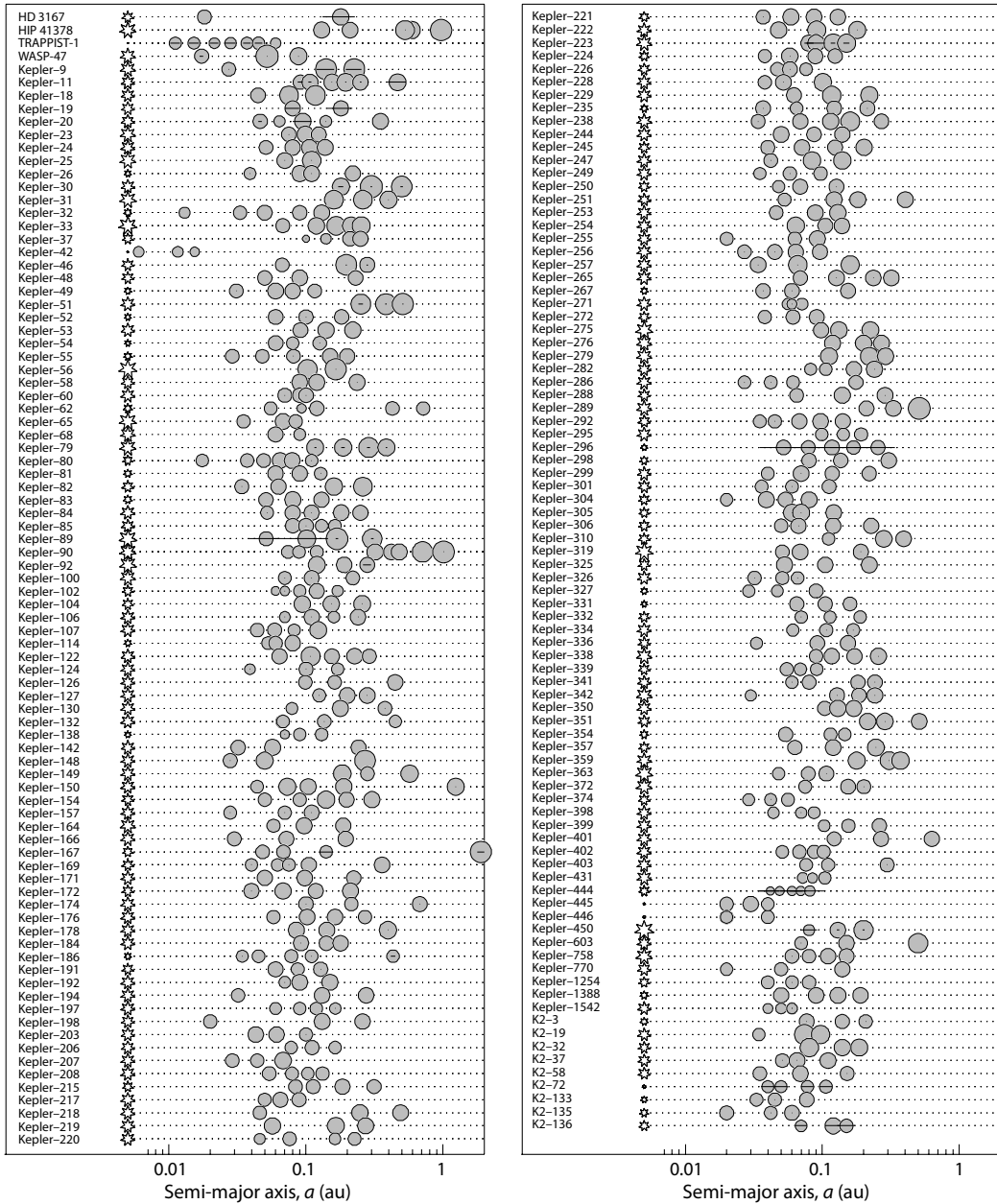


Figure 6.114: Transit discoveries for 602 planets in 173 systems, of multiplicity 3 or higher, from the NASA Exoplanet Archive, 2017 December 31. The host star mass is indicated at left with size  $\propto M_*$  (from  $0.1M_\odot$  for TRAPPIST-1 and Kepler-42 to  $1.3M_\odot$  for Kepler-450). Each planet in the system is shown to the right, with sizes  $\propto \log R_p$  (from about  $0.03R_J$  for Kepler-37 b to  $1.15R_J$  for WASP-47 b). Horizontal bars through the planets indicate maximum and minimum star-planet distance from their eccentricities (available only for a few systems). Highest multiplicities are 8 for Kepler-90, 7 for TRAPPIST-1, and 6 for Kepler-11, Kepler-20, and Kepler-80. A similar plot for radial velocity discoveries is given in Figure 2.38.

**High multiplicities** The highest (confirmed) Kepler planet multiplicities are the 8-planet system Kepler-90 (KOI-351; Batalha et al., 2013; Schmitt et al., 2014b; Cabrera et al., 2014; Shallue & Vanderburg, 2018), three 6-

planet systems (Kepler-11, Kepler-20, and Kepler-80), and more than a dozen 5-planet systems.

**Size distribution** Lissauer et al. (2011b) noted a significant trend for smaller planets to be interior to larger

planets (see Figure 6.114). They attributed this to the preferential detectability of small short-period planets. This trend is suggested in their Figures 2–3, and in the enlarged sample of Fabrycky et al. (2014).

Ciardi et al. (2013) corrected the sample for detection and geometric biases, and found that for planet pairs for which one or both objects are approximately Neptune-sized or larger, the larger planet is most often the planet with the longer period. No such size-location correlation is seen for pairs of planets when both planets are smaller than Neptune. Specifically, if at least one planet in a planet pair is Neptune-sized or larger,  $R_p \gtrsim 3R_\oplus$ ,  $68 \pm 6\%$  of the pairs have the inner planet smaller than the outer, while if both planets have  $R_p \lesssim 3R_\oplus$  the fraction is consistent with random planet ordering ( $53 \pm 6\%$ ) with no apparent size hierarchy.

From 909 planets in 355 multi-planet systems, Weiss et al. (2018) found that: (a) similar size progression is confirmed in their larger sample; (b) planets within a given multi-planet system have correlated sizes: each planet is more likely to be the size of its neighbour than a size drawn at random from the distribution of observed planet sizes; (c) systems with three or more planets tend to have a regular spacing: the orbital period ratios of adjacent pairs of planets are correlated; (d) orbital period ratios are smaller in systems with smaller planets; (e) essentially no planets have orbital period ratios smaller than 1.2, regardless of planet size; (f) 93% of pairs are at least 10 mutual Hill radii apart, and that a spacing of 20 mutual Hill radii is most common.

Millholland et al. (2017) also found that planets in a given system have masses and radii far more similar than if it were assembled randomly from planets in the population. This suggests that the compositional scatter in the  $M_p$ – $R_p$  relation is dominated by system-to-system rather than intra-system variance. With enough properties of the star and protoplanetary disk, there may then be a substantial degree of predictability in the outcome of the planet formation process.

**Hypotheses** This size progression, or *size sorting*, may in part arise as a consequence of core accretion, for which models predict that smaller planets form prior to, and interior to, the giant planets (Zhou et al., 2005). Additionally, larger planets formed farther out may migrate inward, shepherding smaller planets inward in the process (Raymond et al., 2008c).

A further effect relevant for close-in planets is photoevaporation, from X-ray and/or extreme ultraviolet irradiation. Lopez & Fortney (2013) derived analytic fits to atmospheric loss rates as a function of extreme ultraviolet irradiation, and the planet's core mass and composition. They suggest that photoevaporation provides a natural explanation for the observations of Ciardi et al. (2013) that inner planets are preferentially smaller, and predict that  $1.8 - 4R_\oplus$  planets should be significantly less common on orbits with  $P < 10$  d.

Hydrodynamic models provide further insight. Owen & Wu (2013) find that photoevaporation only significantly affects low mass planets with H envelopes, being able to remove massive H envelopes inward of  $\sim 0.1$  au for lower mass (Neptune-mass)

objects, while evaporation is negligible for Jupiter-mass objects. They conclude that evaporation is a driving evolutionary force for close-in Kepler planets, with some 50% perhaps having been significantly eroded.

Their models suggest that evaporation explains two prominent observed correlations: a lack of large radius/low density close-in planets, and a bimodal distribution in size with a deficit around  $2R_\oplus$ . Planets that have experienced high X-ray irradiation are generally smaller, having been stripped of their envelopes, while those with lower X-ray exposures are typically larger. To model the observed distribution, they argue that low-mass Kepler planets must be made of rocky cores surrounded by H envelopes, few of them should have initial masses  $> 20M_\oplus$ , and the majority should have cores of a few  $M_\oplus$ .

**Size-ordered entropy** The non-random size-ordering that may have been imprinted by regular formation pathways might be expected to have been eroded by subsequent and more chaotic dynamical evolution. To address whether multi-planet systems retain some ‘memory’ of how they were formed, Kipping (2018) defined the entropy of a planetary system's size-ordering, by first comparing differences between neighbouring planets, and then extending definition to accommodate differences across the entire planet chain. All three proposed definitions of entropy exhibit the expected property that their interval increases with respect to a proxy for time. He found that the observed Kepler multi-planet systems display a highly significant deficit in entropy compared to a randomly generated population, robust against the possibility of missing planets, thus demonstrating some ‘memory’ of their early formation.

To illustrate the principles, Kipping (2018) takes as examples the ostensibly ordered 5-planet system Kepler–80 (in terms of planets size-ordered outwards), and a disordered system like the 5-planet Kepler–20 (see his Figure 1). In his simplest definition of size-ordering entropy, changes between neighbouring planets are assigned a tally +1 if the outer planet is larger than the inner, and –1 otherwise. The tally total is a simplistic quantifier of the system's entropy quantified by planet size.

### 6.30.2 Hill stability

Multi-planet systems are, in general, presumed to be dynamically stable over time scales comparable to the lifetime of the star.

Unless two bodies are resonantly locked in a configuration that allows for crossing orbits (such as Neptune and Pluto), the bodies will undergo dynamical instability if their eccentricities are too great and their semi-major axis difference is too small. Planets whose orbits never cross are said to be *Hill stable* (Hill, 1878), and they obey the inequality (Gladman, 1993)

$$\frac{1 + \eta_1 + \eta_2}{(\eta_1 + \eta_1\eta_2 + \eta_2)^3} \left[ \eta_1 + \frac{\eta_2}{\alpha} \right] \times \left[ \eta_2 \sqrt{\alpha(1 - e_2^2)} + \eta_1 \sqrt{1 - e_1^2} \right]^2 > 1 + \frac{3^{\frac{4}{3}} \eta_1 \eta_2}{(\eta_1 + \eta_2)^{\frac{4}{3}}} - \frac{\eta_1 \eta_2 (11\eta_2 + 7\eta_1)}{3(\eta_1 + \eta_2)^2}, \quad (6.173)$$

where  $\eta_1 \equiv m_1/m_0$ ,  $\eta_2 \equiv m_2/m_0$ , and  $\alpha = a_2/a_1$ . Systems which do not satisfy this condition may still be stable, but typically this is true only for resonant systems.

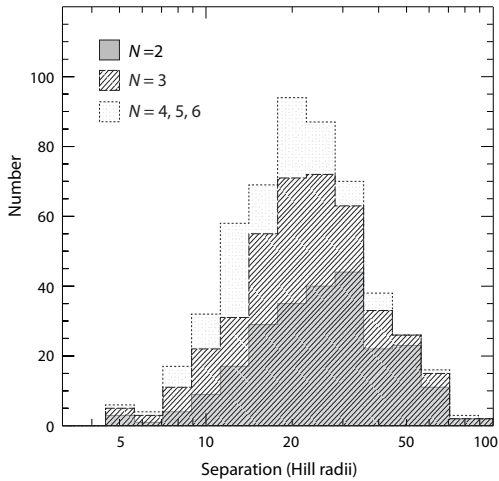


Figure 6.115: Separations of nearest neighbours in the Kepler multi-planet systems, measured in Hill radii (Equation 6.174), from the catalogue of Fabrycky et al. (2014). Masses are derived using the mass–radius relation  $M_p = M_\oplus (R/R_\oplus)^\alpha$  with  $\alpha = 3$  for  $R_p < R_\oplus$  and  $\alpha = 2.06$  for  $R_p > R_\oplus$ . Planets on circular, co-planar orbits separated by more than 9–12 Hill radii are expected to be stable for the lifetime of typical stars; the few planet candidates seen with smaller separations may have large errors in their estimated radii, may not obey the assumed mass–radius relation, or may not be planets orbiting the same star. From Lissauer et al. (2014a, Figure 4), by permission from Nature/Springer/Macmillan Ltd, ©2014.

Rigorous stability criteria are only available for 2-planet systems (Gladman, 1993), but a useful approximation is that systems composed of planets on nearly circular, nearly co-planar orbits are stable over  $N \gg 1$  orbits if the separation between adjacent planets,  $a_{i+1} - a_i$ , exceeds some constant  $K_N$  times the mutual Hill radius,  $R_H$ , the separation at which the mutual planetary gravity equals the difference in the pull of the star on the two planets (Hill, 1878; Smith & Lissauer, 2010; Lissauer et al., 2011b)

$$R_{H,i,i+1} \equiv \left( \frac{M_i + M_{i+1}}{3M_\star} \right)^{1/3} \frac{a_i + a_{i+1}}{2}, \quad (6.174)$$

where  $M_i$  and  $a_i$  are the planetary masses and semi-major axes,  $M_\star$  is the central star mass, and the masses of interior planets have been neglected. For  $N = 10^{10}$ ,  $K_N \approx 9\text{--}12$  (Smith & Lissauer, 2009).

Most Kepler multi-planet systems lie comfortably within this stability criterion (Figure 6.115). Numerical integrations assuming initially circular, co-planar orbits also confirm that virtually all are stable for  $\gtrsim 10^{10}$  orbits (Lissauer et al., 2011b; Fabrycky et al., 2014). Details depend on the assumed mass–radius relation, but are relatively insensitive to it since  $R_H \propto M_p^{1/3}$  (Equation 6.174).

The dynamics of 2-planet systems are a special case of the 3-body problem, amenable to analytic treatment and simple numerically-derived scaling formulae. For

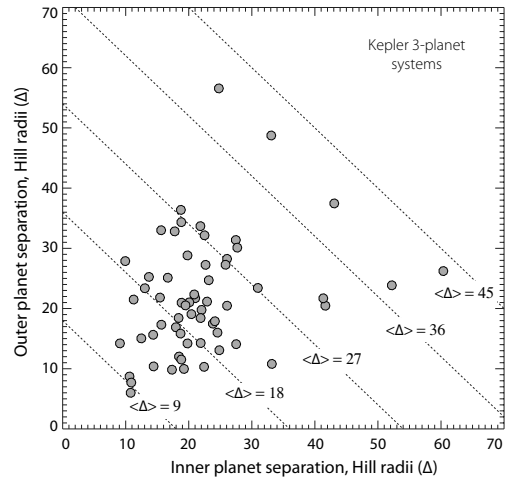


Figure 6.116: Neighbour separation, in mutual Hill radii, in the 3-planet systems studied by Johansen et al. (2012). The 3-planet stability criterion for Earth-mass planets is  $\langle \Delta \rangle \sim 9$ . Masses are based on the empirical mass–radius relationship of Tremaine & Dong (2012, as given in Equation 6.161). From Johansen et al. (2012, Figure 9), by permission of IOP Publishing/AAS.

example, a pair of planets initially on co-planar circular orbits with dynamical orbital separation

$$\Delta \equiv \frac{a_o - a_i}{R_H} > 2\sqrt{3} \approx 3.46 \quad (6.175)$$

can never develop crossing orbits, and are thus Hill stable (Gladman, 1993). Lissauer et al. (2011b, Table 2) gives the dynamical orbital separations of planet pairs in 2-planet systems from the first 4-month catalogue, and all obey this criterion.

The 16-month catalogue of Batalha et al. (2013) contained 84 3-planet systems. Johansen et al. (2012) examined the mutual separation of a selected sample of 62. The mutual separation of the outer and inner neighbouring pairs, in units of their mutual Hill radii, are shown in Figure 6.116. Masses are based on a simple mass–radius relation suggested by Tremaine & Dong (2012), and given in Equation 6.161.

All systems in Figure 6.116 were found to be stable, or at the edge of stability, over  $10^9$  yr. The maximum mean Hill separation is  $\Delta \approx 45$ , but 89% have  $\langle \Delta \rangle < 30$ . The lack of systems of large Hill separation is at least in part an observational bias, since widely spaced systems are less likely to be observed in triple transit.

### 6.30.3 Dynamical stability

The actual dynamical stability of planetary systems also depends on the eccentricities and mutual inclinations, none of which can be measured well from the transit data alone. Circular co-planar orbits have the lowest angular momentum deficit (§10.9.2), and thus are the most stable (Laskar, 1997; Laskar & Petit, 2017). An exception



exists for planet pairs protected by mean motion resonances that produce libration of the relative longitudes of various combinations of orbital elements and prevent close approaches. Hence, the Kepler data can only be used to suggest that a pair of planets is not stable. Instability is particularly likely if their semi-major axes are closer than the resonance overlap limit (Wisdom, 1980; Malhotra, 1998; Lissauer et al., 2011b)

$$2 \frac{a_o - a_i}{a_i + a_o} < 1.5 \left( \frac{M_p}{M_\star} \right)^{2/7}. \quad (6.176)$$

Systems with more than two planets have additional dynamical complexity, but are unlikely to be stable unless each neighbouring pair of planets satisfies Equation 6.175. Lissauer et al. (2011b) calculated these nominal dynamical separations between neighbouring planet pairs in Kepler systems with 3 or more planets, finding that in the overwhelming majority of cases, the inequality is satisfied by a large factor.

For the 4-month data, Lissauer et al. (2011b) investigated the long-term stability of all 55 systems with three or more planets, extending over  $10^{10}$  orbital periods of the innermost. They found all to be stable, except Kepler-487 and Kepler-132. For the most populous (6-planet) system, Kepler-11, the (all-circular) fit remained stable for the full integration of 1 Gyr.

For the 16-month data release, Fabrycky et al. (2014) assessed the fidelity of the multiple candidates as true planetary systems based on the apparent orbital stability. They also found that the candidates avoid close orbital spacings that would lead to instability, and concluded that 85–99% of the candidate pairs are really pairs of planets orbiting the same star. They also confirmed the findings that most planetary systems are not resonant, but that the distribution of planet period ratios shows clumping just wide of the 2:1 and 3:2 (first-order) resonances, with a gap just interior to them.

Other related dynamical, stability, and compactness studies have been reported (e.g. Mahajan & Wu, 2014; Hobson & Gomez, 2017).

**Eccentricity versus multiplicity** Studies of radial velocity detected systems have shown a quantified anticorrelation between the system multiplicity and orbital eccentricities (§2.10.4). Similar results were found for a large and homogeneous sample of 698 Kepler planets with eccentricities estimated from transit duration statistics (Xie et al., 2016, see also §6.26.2). The correlation was further studied and confirmed using both radial velocity and transit discoveries by Zinzi & Turrini (2017).

**Dynamical packing** The degree of ‘packing’ in planetary systems has important implications for their origin and evolution. It has been codified in the *packed planetary systems hypothesis* (e.g. Barnes & Quinn, 2004; Raymond & Barnes, 2005; Raymond et al., 2006a; Barnes

& Greenberg, 2007b), which asserts that (many) planetary systems are dynamically packed, or ‘filled to capacity’. In a dynamically ‘full’ or ‘packed’ system, no additional planets, even of very small mass, could be inserted between the existing ones while maintaining a stable configuration. Amongst these are the Kepler ‘systems with tightly-packed inner planets’, or STIPs (Lissauer et al., 2011b; Payne et al., 2013), notable examples being Kepler-11, Kepler-36, Kepler-80, and Kepler-90. These may, nonetheless, stably support *satellites* across a range of parameter space, only slightly decreased compared to that for single planets (Payne et al., 2013).

Dynamically packed systems are a natural consequence of models in which planets grow hierarchically, since planet growth should stop once all of the orbits are stable. However, the correspondence is not exact, since stable zones may not be occupied if the planets they contained collided in the final stages of hierarchical growth; moreover, the system may contain additional planets that are not transiting or fall below the Kepler detection threshold. The evidence (Figure 6.115) suggests that the known Kepler planets are typically separated by about twice the distance required for stability, but given the possible presence of undiscovered planets and the destabilising effects of non-zero eccentricity, many of these systems may be dynamically packed (Fang & Margot, 2013).<sup>6</sup>

Fang & Margot (2012b) applied the packed planetary systems hypothesis, using a Hill stability criterion to identify eight two-planet systems with significant gaps between the innermost and outermost planets. For each of these systems, they performed long-term numerical integrations of  $10^7$  yr to investigate the stability of 4000–8000 test particles injected into the gaps. They mapped out stability regions in orbital parameter space  $a, e$ . Strong resonances can add additional regions of stability in an otherwise unstable parameter space.

They derived expressions for the extent of the stability regions, in terms of the dynamical spacing,  $\Delta$ , the separation between two planets in units of their mutual Hill radii. Their results suggest that planets with separation  $\Delta < 10$  are unlikely to host extensive stability regions, and that about 95 out of 115 two-planet systems may have sizeable stability regions.

Specifically, Fang & Margot (2012b) predicted that various systems, including Kepler-10, Kepler-55, Kepler-111, Kepler-121, Kepler-309, Kepler-553, and Kepler-598, may be harbouring additional planets or low-mass bodies between the inner and outer detected planets. For Kepler-55, a subsequent candidate list (Batalha et al., 2013) and confirmation analysis (Rowe et al., 2014), actually identified three additional planets, two of which are in their predicted stability zone.

From a sample of Kepler candidate planets with  $P < 200$  d and  $R_p = 1.5 - 30R_\oplus$ , Fang & Margot (2013) found that, on average, neighbouring planets are separated by  $21.7 \pm 9.5$  mutual Hill radii, consistent with that of adjacent planets in the solar system. They determined the fraction that are dynamically packed by performing long-term ( $10^8$  yr) simulations with an additional planet inserted on an intermediate orbit.

<sup>6</sup> In the solar system, the region from Jupiter to Neptune is packed, or nearly so (Holman, 1997), but inside Mercury, and between Earth and Mars, there are significant bands in semi-major axis where additional low-mass planets would be stable for  $\geq 10^8$  yr (Evans & Tabachnik, 2002).

From those exhibiting instability they derived lower bounds of  $\geq 31\%$ ,  $\geq 35\%$ , and  $\geq 45\%$  of 2-planet, 3-planet, and 4-planet systems that are dynamically packed, suggesting that many are indeed filled to capacity, and providing another constraint that formation and evolution models must satisfy.

Pu & Wu (2015) found that observed spacings are tightly clustered around 12 mutual Hill radii, while the minimum spacing for similar mass systems to survive dynamically for 1 Gyr is  $\sim 10$  if orbits are circular and coplanar, and  $\sim 12$  for  $e \sim 0.02$ . They concluded that typical systems were formed with even tighter spacing, but most, except the widest, have undergone dynamical instability, resulting in fewer planets and larger spacings. In this case, the high-multiple systems (five or more transiting planets) are primordial systems that remain stable, the abundant single or double planetary systems may be the descendants of more closely packed high-multiple systems.

In the simulations of Obertas et al. (2017) isolated systems of up to five Earth-mass planets can fit in the habitable zone of a Sun-like star, without close encounters, for at least  $10^9$  orbits.

Efficient machine-learning algorithms to characterise the stability boundaries of tightly-packed systems over  $\sim 10^7$  orbits have been demonstrated (Tamayo et al., 2016b).

#### 6.30.4 Resonances in the Kepler systems

The distribution of observed period ratios shows that the majority of candidate pairs are neither in, nor near, low-order mean motion resonances. Nonetheless, there are small but statistically significant excesses of pairs that are in resonance, as well as those spaced slightly too far apart to be in resonance, particularly near the 2:1 resonance. This conclusion is supported by the analysis of transit timing variations for a subset of systems, which also allows the determination of  $e$  and  $M_p$  in certain favourable cases (Section 6.20).

To guide the following discussions, Figure 6.117 shows the mass and radius ratios of all systems observed to be in or near mean motion resonance, both transiting and radial velocity, as of 2016.

Rein (2012) used N-body simulations of multi-planet systems resembling those observed by Kepler to argue that the observed period ratio distribution is inconsistent with either smooth (type I/II) or stochastic migration forces acting alone. However, applying both stochastic and smooth migration forces to the planets simultaneously results in a period ratio distribution similar to that observed. This is a natural scenario if planets form in a turbulent protoplanetary disk where these forces are always present. The observed period ratio and eccentricity distribution can in principle constrain the relative strength of these forces.

Wang & Ji (2014) performed simulations of the 3:2 and 2:1 mean motion resonance systems (representing some 7% and 18% of their 222 candidate 3-planet systems), and found that the populations can be explained by a combination of stellar accretion rate, stellar magnetic field, migration speed, and additional planets.

**Background** The physics of orbital resonances, and some of the observational consequences, is summarised

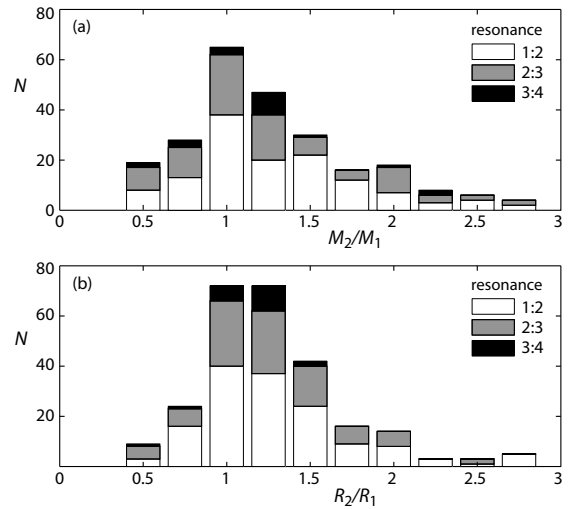


Figure 6.117: Distributions of (a) the mass ratio, and (b) the radius ratio of near mean motion resonance planet pairs (subscripts 1 and 2 denote the inner and outer planets). The figure includes all multi-planet systems with pairs in or near mean motion resonance with  $\Delta < 0.2$ , where  $\Delta = (j-1)P_2/(jP_1) - 1$ ,  $j = 2, 3, 4$ , and  $P_1$  and  $P_2$  are the corresponding periods. Data is from `exoplanet.org` as of 2016. From Wu et al. (2016a, Figure 1), by permission of IOP Publishing/AAS.

in Section 10.8. Some key features relevant to a consideration of orbital resonances in the Kepler multi-planet systems are given here (Veras & Ford, 2012).

The behaviour of linear combinations of orbital angles from each of the two planets determines if a system is in resonance or not. *Libration* is a term denoting oscillation of a resonant angle, while *circulation* implies the absence of oscillation. Resonant systems must have a librating angle; for mean motion resonances the librating angle incorporates the positions of both planets. This seemingly simple criterion belies the complex behaviour often seen in real systems.

For example, Brasser et al. (2004) illustrate how the resonant angle of a Neptunian Trojan can switch irregularly between libration and circulation, while Farmer & Goldreich (2006) illustrate how long periods of circulation can be punctuated by short periods of libration. Characterising libration versus circulation in exoplanet systems, often with two massive extrasolar planets, may require careful statistical measures (Veras & Ford, 2010).

The gravitational potential between two co-planar bodies orbiting a star can be described by two ‘disturbing functions’,  $R_w$ , with  $w = 1, 2$ , which are infinite linear sums of cosine terms with arguments of the form

$$\phi(t) = j_1 \lambda_1(t) + j_2 \lambda_2(t) + j_3 \tilde{\omega}_1(t) + j_4 \tilde{\omega}_2(t), \quad (6.177)$$

where  $\lambda$  is the mean longitude,  $\tilde{\omega}$  is the longitude of pericentre,  $j$  are integer constants, and subscripts 1 and 2 refer to the inner and outer bodies.

A variety of mean motion resonances are known to exist in the solar system (box, page 678), and also in exoplanet systems discovered through radial velocity measurements (§10.8). For most of these,  $M_p$ ,  $e$ , and  $\omega$  have been measured directly. Contrastingly, for Kepler systems, these parameters are poorly constrained, if at all. Quantifying the frequency of resonant Kepler systems consequently poses particular challenges.

The absence of resonance may be as important in probing planet formation and evolution, for example in systems with tightly packed but stable configurations (Lissauer et al., 2011a), or in systems which might feature transit timing variations that span several orders of magnitude (Ford et al., 2011; Veras et al., 2011a).

Resonances may be a signature of a particular mode of planetary formation, specifically convergent migration in nascent protoplanetary disks (Thommes & Lissauer, 2003; Kley et al., 2004; Papaloizou & Szuszkiewicz, 2005). Their absence might be indicative of a dynamical history dominated by gravitational planet–planet scattering (Raymond et al., 2008a). Resonant statistics are expected to illuminate the processes of disk evolution and gravitational scattering (Matsumura et al., 2010b; Moeckel & Armitage, 2012).

**Period ratios and resonances** Lissauer et al. (2011b) examined all planet period ratios in Kepler systems, and presented distributions and statistics linking the periods to potentially resonant behaviour. A corresponding analysis for a later data release is described by Fabrycky et al. (2014).

Lissauer et al. (2011b) concluded that most multiple Kepler planet candidates are neither in, nor very near to, mean motion orbital resonances. Nonetheless, such resonances and near resonances are more numerous than would be the case if period ratios were random. First-order resonances dominate, but second-order resonances are present.

There appear to be at least three classes of resonance-related relationships present: (1) the most abundant are planet pairs that have period ratios from one to a few percent larger than those of nearby resonances; (2) some planet pairs, as well as chains of three or more planets, have orbital periods within one part in 1000 of exact first-order resonance ratios; (3) a few planet pairs deviate from exact period ratios by  $\sim 1\%$ , but appear to be protected from close approaches by resonantly-librating configurations.

Veras & Ford (2012) developed an algebraic method to determine which Kepler two-planet systems *cannot* be in a low-order mean motion resonance, by identifying when any potentially resonant angle of a system must circulate. They determined the proximity of all two-planet systems to a mean motion commensurabil-

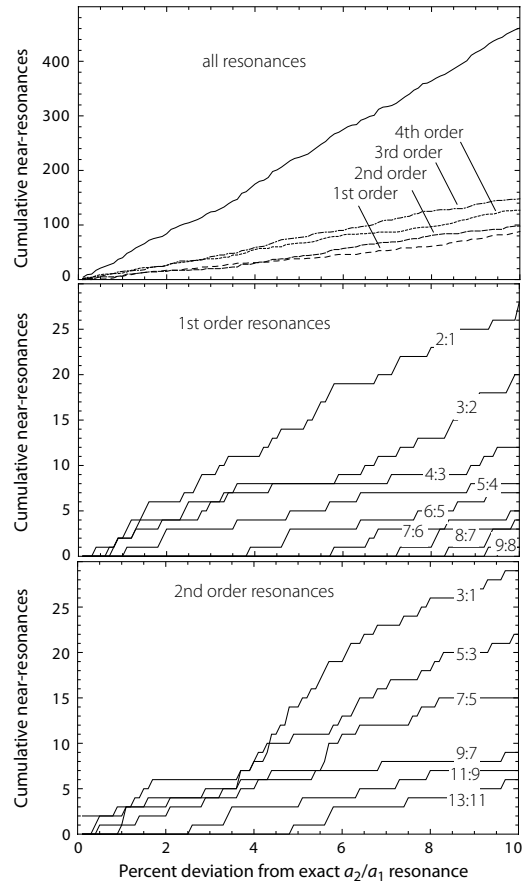


Figure 6.118: Near-resonances in the 2-planet Kepler (and KOI) systems. The cumulative number of  $j_1:j_2$  systems is shown as a function of the proximity parameter  $x$  (Equation 6.178). The upper panel includes all 1st–4th order resonances, and the lower two show the subsets of 1st and 2nd-order resonances. From Veras & Ford (2012, Figure 2), © Oxford University Press.

ity, up to fourth order, through

$$\left(1 - \frac{x}{100}\right) \left(\frac{j_1}{j_2}\right)^{\frac{2}{3}} < \frac{a_1}{a_2} < \left(1 + \frac{x}{100}\right) \left(\frac{j_1}{j_2}\right)^{\frac{2}{3}}, \quad (6.178)$$

where  $x$  measures the percentage offset from resonance in semi-major axis space; any given planetary system may be close to several resonances. They refer to a *near-resonant instance* as a case where this condition is satisfied. The cumulative frequency of near-resonant instances as a function of  $x$  (Figure 6.118) demonstrates the wide spectrum of possible resonances, depending on its precise definition.

They found that of 116 Kepler systems with two transiting candidates, 94 have planets with periods similar enough to be considered ‘near-resonant’ for at least one first- to fourth-order resonance with  $x \leq 10$ . These 94 systems registered a total of 465 near-resonant instances for  $j_1 < 20$ , of which 313 cannot be resonant.

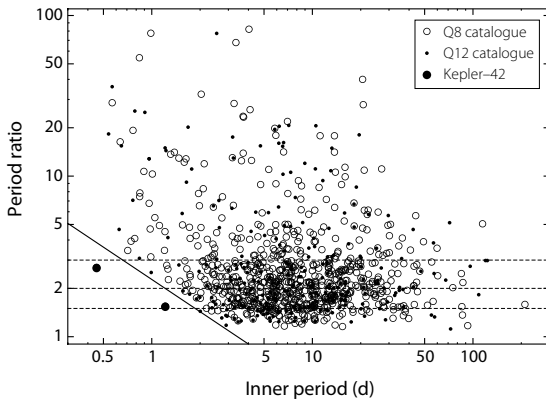


Figure 6.119: Period ratios for adjacent Kepler planets as a function of the orbital period of the inner planet. Horizontal lines are the 3:2, 2:1, and 3:1 mean motion resonances. The diagonal line is given by  $P_2/P_1 = 2.3(P_1/d)^{-2/3}$ . Open circles are planet pairs from the Kepler Q8 catalogue, small dots are new systems or planets in the Q12 catalogue, and the large filled circles indicate the Kepler-42 system. From Steffen & Farr (2013, Figure 1), by permission of IOP Publishing/AAS.

For 20 systems, resonance could not be ruled, while the remaining 70 systems cannot be in resonance, despite their close proximity to commensurability. These non-resonant cases include the tightly-packed 5-planet system Kepler-271 which possesses 15 near-resonant instances. Their results support the argument that a high fraction of systems may be *near* resonance, but not actually *in* resonance.

Steffen & Farr (2013) noted the lack of close-proximity multi-planet systems with orbital periods less than a few days, with the exception of Kepler-42 (Figure 6.119). The absence is presumably related to some unmodeled effects of tides, disk interactions, winds, general relativity, or magnetic fields. Other studies of the period-ratio and mass-ratios of adjacent pairs are given by Jiang et al. (2015).

**Pile-up near resonance** A notable feature of the Kepler systems is that while the spacing between planets appears to be roughly random, there is a distinct pile-up of planet pairs just wide of certain (low-order) resonances, and a nearly empty gap just narrow of them (Lissauer et al., 2011b; Fabrycky et al., 2014; Chatterjee & Ford, 2015; Steffen & Hwang, 2015). Lithwick & Wu (2012) proposed that dissipation drives this asymmetry, via an effect they referred to as *resonant repulsion* (see also Delisle et al., 2012; Batygin & Morbidelli, 2013b).

Their explanation rests on the fact that the eccentricity of planets near resonances can be separated into two parts (§6.20.4): a part that is forced by the resonance and is determined by the planets' proximity to resonance, the *forced eccentricity*, or *forced resonant eccentricity* to distinguish it from the more commonly used forced sec-

ular eccentricity (cf. Murray & Dermott, 2000), and a part that is unrelated to the resonance, the *free eccentricity*. Any dissipation damps the free eccentricities, but the forced eccentricities persist as long as the planets remain close to resonance. As dissipation continually acts on the forced eccentricities, it extracts energy from the planet orbits, and pushes apart any planet pair that happens to lie near resonance, resulting in planet pairs just wide of resonance (Papaloizou, 2011).

The model does not succeed in explaining all systems, and investigations continue (e.g. Silburt & Rein, 2015), with more complex behaviour, including resonance crossings, resulting from mass accretion during migration (Wang & Ji, 2017).

**Stochastic migration** Stochastic impulses experienced by planets during their migration, or *stochastic migration* (§10.5.1), can also break some of the early, widely spaced resonances, leading to the formation of compact configurations in less massive and more realistic disks. Various physical mechanisms have been invoked to create such stochastic kicks, with turbulent density fluctuations in a protoplanetary disk with magnetorotational instability being a leading contender. For example, detailed simulations support the scenario in which gravitational interactions and collisions with embryos can account for both the present proximity of the Kepler-36 planets, and their large density contrast (§10.7.3).

**Resonance chains** Nearly-exact mean motion resonances are not common in the Kepler sample (Lissauer et al., 2011b), and a few are particularly noteworthy.

*Kepler-29* and *Kepler-232*: 2-planet systems with period ratios deviating from an exact 9:7 resonance by 1 part in 5000 and 1 in 500 respectively. The 9:7 resonance can be fairly strong if one or both planets have a significant eccentricity, or if their orbits are significantly inclined.

*Kepler-60*: a complex dynamical system, with 3 super-Earths, which exhibits close commensurabilities which may be a chain of 2-body, first-order mean motion resonances, or a true 3-body (Laplace) mean motion resonance with none of the two-body critical angles librating (Papaloizou, 2015; Goździewski et al., 2016).

*Kepler-79*: three hot super-Earths near a 4:2:1 mean motion resonance (Wang et al., 2012b).

*Kepler-80*: a 6-planet system with periods 0.99, 3.07, 4.65, 7.05, 9.52, and 14.6 d. Neighbouring pairs of the middle four have period ratios about 1% greater than those of first-order two-body mean motion resonances. The combinations of mean motions  $2n_2 - 5n_3 + 3n_4 \approx 1.6 \times 10^{-5}$  and  $2n_3 - 6n_4 + 4n_5 \approx 1.3 \times 10^{-5}$  suggest that two 3-body Laplace-like resonances (§10.8.3) and/or a 4-planet resonance may control the dynamics (Lissauer et al., 2011b; MacDonald et al., 2016). Subsequent discovery of the sixth (outermost) planet, planet g, ap-

pears to continue this Laplace resonance chain (Shallue & Vanderburg, 2018), and provides somewhat independent confirmation of its reality.

*Kepler-90*: an 8-planet system, in which planets b and c are within 0.5% of the 4:5 mean motion resonance, planets d, e, and f are close to a 2:3:4 mean motion resonance chain (Batalha et al., 2013; Cabrera et al., 2014; Schmitt et al., 2014b).

*Kepler-223*: a 4-planet system with periods (7.3, 9.8, 14.8, and 19.7 d) in the ratio 8:6:4:3 to 1 part in  $10^3$  (Fabrycky et al., 2011; Moore et al., 2013). This precision resonance chain suggests that planets migrating in a gas disk can avoid close encounters, eventually converging to a stable close-packed configuration (Delisle, 2017). The system remains difficult to study due to the faintness of the star ( $K_p = 15.34$ ), and the small transit depths.

*K2-138*: a 5-planet system of sub-Neptune mass ( $1.6 - 3.3R_{\oplus}$ ), orbiting a  $V = 12.2$  K dwarf, and discovered by Citizen Scientists (Christiansen et al., 2018). With periods 2.35, 3.56, 5.40, 8.26, and 12.76 d, it represents an unbroken chain of near 3:2 resonances. Predicted 2–5 min transit timing variations may be observable by Spitzer or CHEOPS, and the system is bright enough for planet mass determinations by radial velocity measurements.

Resonance chains probably developed in three stages (see §10.7.3): planet formation in a protoplanetary disk far from the star, inward migration and mean motion resonance trapping due to interaction with the gas disk, followed by tidal circularisation due to the central star.

For example, convergent migration including the effects of eccentricity damping, gas drag, and both type I and type II migration of planetesimals, planetary embryos, and giant planets successfully reproduce the near 4:2:1 mean motion resonance configurations observed in Kepler-238 and Kepler-302 (Sun et al., 2017b).

Simulations including mass accretion and potential outward migration have been successful in replicating the near-resonance chains in Kepler-48, Kepler-53, Kepler-100, Kepler-192, Kepler-297, Kepler-399, and Kepler-450 (Wang & Ji, 2017).

Chain breaking, which has been suggested as a mechanism leading to the creation of the hot super-Earth systems, is discussed in Section 10.7.3.

**Laplace resonance** Libert & Renner (2013) assessed the signature of a co-planar Laplace-resonant 3-planet system (§10.8.3) on observable transit timing variations over 100 yr, on the assumption that only the inner planet transits. The signature for an inner giant planet perturbed by two terrestrial companions comprises three periods: two associated with the Laplace-resonant angle, and a third with the precession of pericentres (Figure 6.120). Inclined Laplace-resonant systems may also be detectable, of interest since the possible formation of (highly) inclined two- and three-body resonant systems

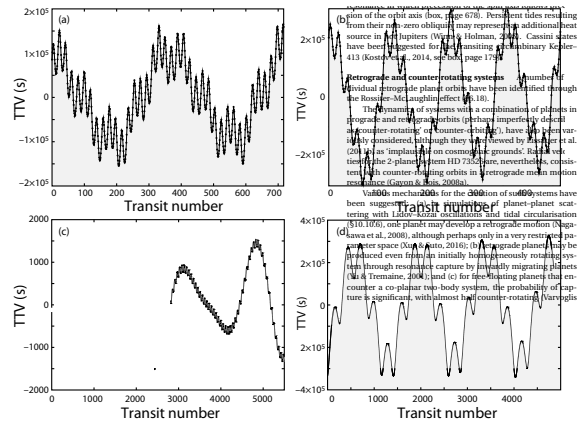


Figure 6.120: Transit Timing Variations (TTV) in seconds versus Transit number for various exoplanet systems. The figure consists of four panels (a, b, c, d) showing TTV plots. Panel (a) shows Kepler-90 with TTV up to  $2 \times 10^6$  s over 700 transits. Panel (b) shows Kepler-223 with TTV up to  $2 \times 10^3$  s over 5000 transits. Panel (c) shows K2-138 with TTV up to  $2 \times 10^3$  s over 5000 transits. Panel (d) shows a system with TTV up to  $4 \times 10^3$  s over 4000 transits. Each panel includes a legend for 'retrograde and counterrotating systems' and 'retrograde and counterrotating systems'.

(b) of the orbit axis (from page 678). Persistent tides resulting from their relatively small obliquity may represent an additional heat source in the Jupiters (Wang & Holman, 2004). Cassini states have been suggested for the Jovian system (see the arbitrary Kepler-413 (Kozlov et al., 2014, arXiv:1405.0004, page 19)).

retrograde and counterrotating systems. The dynamics of systems with a combination of planets in retrograde and retrograde orbits (through supercritical defects) counter-rotating or counter-rotating, have been previously considered, although they were neglected by Fabrycky et al. (2011) as 'implausible on cosmological grounds'. Fabrycky et al. (2011) also considered the 2-planet system HD 73529, where, nevertheless, consistent counter-rotating orbits in retrograde mean motion resonance (Gajda & Bal, 2009a).

Valid mechanisms for the detection of such systems have been suggested. In the case of planet-planet scattering with tidal circularisation and tidal circularisation (Sills et al., 2008), one planet may develop a retrograde motion (Gajda et al., 2008), although perhaps only in a very restricted parameter space (D'Amico, 2016). In retrograde planets may be produced even from an initially homogeneously rotating system through resonant capture by inwardly migrating planets (Wu & Tremaine, 2006); and (c) for free-floating planets that encounter a co-planar two-body system, the probability of capture is significant, with almost half counter-rotating (see Fig. 6.120).

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et al., 2012), somewhat analogous to the formation of irregular satellites in the solar system (§12.5.10).

Problems of formation aside, Smith & Lissauer (2009) found that systems in which alternate planets orbit in different directions can be packed much more closely than prograde systems, and with much longer dynamical survival times.

**Unseen outer giants** Using an N-body code with additional forces to emulate the effects of a protoplanetary disk, Hands & Alexander (2016) performed dynamical simulations of the assembly of compact systems of super-Earth-mass planets with unseen giant companions, viz. analogous to Kepler-11 or Kepler-32 in that they contain four or five inner super-Earths, but also containing longer-period giant companions unlikely to have been detected by Kepler. They found that giant companions tend to break widely spaced first-order mean motion resonances, allowing the inner planets to migrate into tighter resonances, leading to more compact architectures, and increasing the occurrence rate of Laplace resonant chains.

### 6.30.5 Mutual inclinations of multi-planet systems

**Introduction** The high degree of co-planarity of the solar system orbits (§12.4.2) has long been recognised as an important constraint on models of planet formation (Kant, 1755; Laplace, 1796). However, despite its fundamental role in planetary dynamics, mutual inclinations in multi-planet systems are generally poorly known.

This continues to be true in multiple transiting systems (Lissauer et al., 2011b). Even though the inclinations to the line-of-sight of all transiting planets must be small, the orbits in any individual system could be rotated around the line-of-sight, and so be mutually inclined (a semi-analytical method for calculating the probability that two mutually inclined planets are observed to transit, and applied to the Kepler dichotomy (§6.30.6), is given by Read et al., 2017). Other non-transiting planets in the same system may also orbit at arbitrary mutual inclinations.

Low orbit inclinations may be expected in formation models invoking growth within a dissipative protoplanetary disk (§10.4.1). However, subsequent disk interactions (§10.10.2), planet–planet scattering (§10.10.4), and forcing by distant perturbers (§10.10.6), will all leave their signatures in the eccentricity–inclination distribution of exoplanet systems. Mutual inclinations therefore provide important but inadequately measured constraints on formation theories.

Relative inclinations can be determined or constrained in various ways: from astrometry, with some measurements obtained with HST-FGS (§3.7), and many more expected from Gaia (§3.9); from transiting systems with non-transiting companions detected from radial velocity measures, or transit timing variations (§6.20); from the Rossiter–McLaughlin effect of planets in the same system (§6.18); from measurements of the true obliquities (§8.3.2); from the transit behaviour in systems with star spots (§6.14.2); from the geometry of

planet–planet eclipses (§6.14.16); from changes in transit time variations (§6.20); and from changes in transit duration and depth (§6.20.10).

The discussions below focus on multi-planet systems orbiting single star hosts. In addition, there are several circumbinary systems where the planet is slightly mutually inclined to the binaries and exhibit significant precession effects, but all such systems currently known have low mutual inclinations,  $\Delta i \lesssim 5^\circ$  (§6.31).

**Direct constraints from Kepler** From photometry alone, the absolute nodal angle of orbits on the sky is undetermined (cf. Figure 2.2). Accordingly, only relative angles can be constrained, specifically from dynamical interactions or, occasionally, from mutual transits.

Mutual inclinations can be measured by the change in transit duration and depth as a function of time due to nodal or apsidal precession (§6.19.4). Orbits that are highly misaligned, and/or highly eccentric, will precess more rapidly, causing the transit chord to move across the face of the star, and changing the transit duration. Combining ingress/egress information with transit timing variations (§6.20) and duration/depth changes (§6.20.10) can give full three-dimensional information on the system, up to an unknown rotation in the plane of the sky (Mills & Fabrycky, 2017a).

Individually constrained systems, typically in low- $e$  and often resonant orbits (as for GJ 876, §2.12.4), are generally rather flat,  $\Delta i \lesssim 10^\circ$ . These include: Kepler-9 bcd, from an absence of transit duration variations (Holman et al., 2010); Kepler-10 bc (Batalha et al., 2011; Fressin et al., 2011); Kepler-11 b–g, from an absence of transit duration variations (Lissauer et al., 2011a); Kepler-30 bcd from star spots (Sanchis-Ojeda et al., 2012); Kepler-46 bcd from transit timing variations (Nesvorný et al., 2012); Kepler-56 bc from asteroseismology (Huber et al., 2013a); Kepler-117 bc from a photo-dynamical model (Almenara et al., 2015c); and Kepler-419 bc from transit timing variations (Dawson et al., 2014).

**Large mutual inclinations** Only two (single star) multi-planet systems show direct evidence for significant mutual inclinations. The first,  $\nu$  And cd with  $\Delta i \sim 30^\circ$ , is based on astrometric measurements with HST-FGS (§3.7). The second, Kepler-108, has two moderately eccentric Saturn-mass planets with  $P \sim 49$  and 190 d, although orbiting a star with a wide binary companion at  $\sim 300$  au. A comprehensive photo-dynamical analysis yields an estimate of their mutual inclination  $\Delta i = 24_{-8}^{+11}$  deg (Mills & Fabrycky, 2017a).

Dawson & Chiang (2014) provided indirect evidence for large mutual inclinations in five systems comprising eccentric warm Jupiters with eccentric giant companions, based on the premise of Lidov–Kozai oscillations to explain the prevalence of small  $a$ , large  $e$ , and large spin–orbit misalignments driven by the outer companion. Based on each pair’s observed apsidal separations, which cluster near  $90^\circ$ , they infer that each system has mutual inclinations that oscillate between  $35 - 65^\circ$ .

**Statistical constraints** Other investigations of mutual inclinations have examined the statistical properties of compact multi-planet systems, where constraints have been derived from transit durations, joint considerations with radial velocity surveys, and observed multiplicities. As detailed below, the majority of systems are consistent with low ( $\Delta i \lesssim 5^\circ$ ) mutual inclinations.

**Constraints from transit durations** Statistics of coplanarity can be derived, from Kepler, from the transit durations and impact parameters of different planets orbiting the same star. This method exploits the fact that, in a perfectly flat system, more distant transiting planets should have larger impact parameters. Interpretation of this conceptually simple approach is somewhat complicated by orbit eccentricities.

Transit durations can be used as a joint probe of semi-major axes and eccentricities (§6.13.6). For eccentric orbits, the orbital speed departs from the circular case, with the transit duration being inversely proportional to the projected orbital speed (Ford et al., 2008a). Exploiting this requires use of  $M_\star$  and  $R_\star$ , which can be complicated by any systematic errors (Moorhead et al., 2011; Plavchan et al., 2014; Kipping, 2014).

Individual constraints have been possible for a subset of well-characterised stars with high signal-to-noise transits (Kipping et al., 2012b; Dawson & Johnson, 2012). The properties of the star (most importantly  $\rho_\star$ ) can be further constrained by the durations and ingress and egress, especially in systems with multiple planets (Kipping et al., 2012b), in which case more robust estimates of eccentricities can be derived.

From statistics of transit durations in the 4-month KOI catalogue, Moorhead et al. (2011) found evidence for moderate eccentricities among small planets.

Fabrycky et al. (2014) detailed the dependence of transit duration on co-planarity. If all orbits within a system are circular and co-planar,  $b$  and  $a$  are related by (Fabrycky et al., 2014, eqn 12)

$$\frac{b_2}{b_1} = \frac{a_2}{a_1}, \quad (6.179)$$

where subscripts 1 and 2 denote the inner and outer planets. It is therefore expected that  $b_2 > b_1$  in systems where both planets are close to co-planar and both transit. At the other extreme, planets may be sufficiently misaligned to destroy such correlations, which requires typically  $\Delta i \gtrsim R_\star/a$ . In that case, both  $b_1$  and  $b_2$  would be drawn from the same distribution.

Although stellar properties and impact parameters are generally too inaccurate to make these comparisons directly, some information is preserved in the transit durations. In particular, durations from first to fourth contact are generally well-measured and governed by (Fab-

rycky et al., 2014, their §5.1, see also Equation 6.5)

$$t_T \approx 2 \left( (1+r)^2 - b^2 \right)^{\frac{1}{2}} \left( \frac{R_\star}{v_{\text{orb}}} \right), \quad (6.180)$$

where  $r \equiv R_p/R_\star$  and  $v_{\text{orb}} \propto P^{-1/3}$ . Therefore for each planet in a system, the function  $((1+r)^2 - b^2)^{1/2}$  is proportional to the orbital-velocity normalised transit duration  $t_T/P^{1/3}$  (Steffen et al., 2010). The ratio of this quantity for pairs of planets (see Equation 6.7) is the quantity that is precisely measured and is sensitive to the mutual orbit inclination through their relative values of  $b$ .

From Monte Carlo simulations, Fabrycky et al. (2014) concluded that typical mutual inclinations, for the packed systems of small planets probed, lies in the range  $1.0^\circ$ – $2.2^\circ$ , showing that typical Kepler multi-planet systems tend to be quite ‘flat’, as in the solar system, even over a wide range of eccentricities. Fang & Margot (2012a) reached a similar conclusion. This may in turn provide rather direct evidence that most planetary systems formed from a rotating thin disk of gas and dust.

There are exceptions to this general rule. For example, for the Kepler–11 e/g and Kepler–10 b/c pairs,  $b_2$  is smaller than given by Equation 6.179, and the orbits deviate from co-planarity by  $\Delta i > 1^\circ$  and  $5^\circ$ , respectively (Fabrycky et al., 2014).

In most formation models, planets have mean inclinations that are at least half as large as the mean eccentricities (e.g. Ida, 1990), a result which also holds for the planets, asteroids, and Kuiper belt of the solar system. Accordingly, the mean eccentricity of the Kepler planets would be expected to be  $\leq 0.1$  (Fabrycky et al., 2014).

**Constraints from radial velocity surveys** If mutual inclinations are typically larger than  $R_\star/a$ , then transit surveys would miss some of the planets in each system, while Doppler surveys could potentially detect all of them. A constraint on co-planarity can therefore be obtained by requiring consistency between the occurrence of multiple systems in both types of survey.

High eccentricities are common for radial velocity detected giant planets with  $P > 5$ – $7$  d, with the mean for  $P > 10$  d being around  $\langle e \rangle = 0.26$ . Joint consideration of both survey types can hope to address whether the eccentricities and inclinations of the radial velocity planets are larger than those of the Kepler planets in general, or perhaps just of those planets in Kepler’s multi-planet systems in particular, whether radial velocity eccentricities have been over-estimated (Zakamska et al., 2011), or whether exoplanets generally have much larger eccentricities than inclinations (Rafikov & Slepian, 2010).

Tremaine & Dong (2012) developed a statistical measure of the exoplanet multiplicity function (the fraction of stars containing a given number of planets) and inclination distribution from both transit and radial velocity surveys. They found that the Kepler data alone do not constrain the mean inclination of multi-planet systems; even spherical distributions are allowed

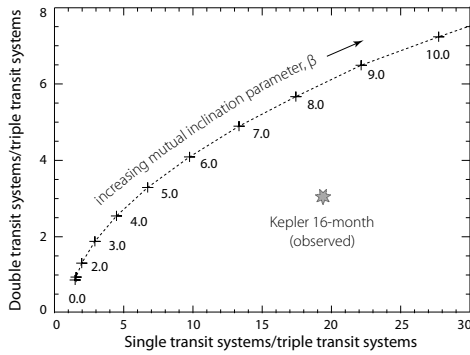


Figure 6.121: The number of double-transit systems from the synthetic 3-planet population of Johansen et al. (2012) versus the number of single-transit systems, for different values of the mutual inclination parameter  $\beta$  (see text). Each is normalised to the number of 3-planet systems in the parent population. The same ratio from the Kepler 16-month data is indicated by a star. No value of  $\beta$  simultaneously yields the observed fraction of double-transit and single-transit systems. From Johansen et al. (2012, Figure 5), by permission of IOP Publishing/AAS.

by the data but only if a small fraction of stars contain very large ( $\geq 30$ ) planet multiplicities (which may be implausible from packing and stability perspectives). Comparing Kepler and radial velocity surveys shows that the mean inclination of multi-planet systems is  $\leq 5^\circ$ , and that the multiplicity function of the Kepler planets is not well determined by present data.

Figueira et al. (2012) compared the properties of planets in systems with  $M_p \sin i > 5 - 10 M_\oplus$  and  $R_p > 2 R_\oplus$  from HARPS and Kepler. If the underlying population is the same, the different detection sensitivities to the orbit inclination probes the planets' mutual inclinations. They considered the frequency of systems with one, two, and three planets detected by HARPS, then varied the mutual inclinations in a given system according to different prescriptions (aligned, Rayleigh distributions, and isotropic) and compared the transit frequencies with those measured by Kepler. Their results suggest that the two data sets are compatible, and better described by a Rayleigh distribution with a mode of  $\leq 1^\circ$ . They concluded planets were likely formed in a disk, and that most planetary systems have evolved quietly without strong angular momentum exchanges, such as those produced by Lidov-Kozai mechanism or planet scattering.

**Constraints from multiplicity** A strong boundary condition on the distribution of mutual inclinations is that any model of the underlying orbital architectures must explain the absolute and relative number of single and multiple transiting systems: the more misaligned a given pair of planets is, the smaller the probability that multiple planets transit, and thus the smaller the fraction of multi-planet systems expected.<sup>7</sup>

<sup>7</sup> The need to distinguish, and avoid confusion, between the number of *transiting* planets in a system, and the number of planets in that system (representing the underlying population), led Tremaine & Dong (2012) to introduce the contraction term *tranet* to denote a transiting planet (as in a 2-tranet 3-planet system to denote a 'double-transiting triple system').

Lissauer et al. (2011b) found that simulated populations generated to match the observed Kepler multi-transiting systems tended to underpredict the observed number of singly-transiting planets, suggesting that, in addition to a population of co-planar systems, there is a distinct population that contains either just one detectable planet per star, or multiple planets with high relative inclinations. Similar results have been found, for example, in simulations of the post-oligarchic assembly phase of G dwarfs and M dwarfs (Hansen & Murray, 2013; Hansen, 2015, §10.4.5).

Johansen et al. (2012) generated a synthetic catalogue of triple-transit systems. For each planet in an initially co-planar 3-planet system they chose  $i$  distributed uniformly between 0 and  $\beta$ , inclined the orbit plane of each planet by this angle, then chose a random angle between 0 and  $2\pi$ , rotating around the axis perpendicular to the original plane to get a random longitude of ascending node and argument of pericentre. They then calculated the probabilities for an observer to see each of the planets transiting by considering 1000 random realisations of each 3-planet system, then calculated the total number of single, double and triple transits.

They found a good match in radii and semi-major axes between the synthetic double and triple transits. However, the synthetic catalogue contained too few single transiting systems, by a factor of 3 (Figure 6.121), and it completely lacks the planets of large radii (between Neptune and Jupiter) found by Kepler.

The inability of the template triple-planet systems to explain simultaneously the double-transit and single-transit systems implies that there is a dichotomy of populations in the underlying planetary systems. On the one hand, there is a population of triple-planet systems with small planets which reproduces all triple-transit and double-transit systems, but only 1/3 of the single-transit systems. An additional population, distinct from the Kepler triple-transit systems, is required to produce the remaining single-transit systems.

### 6.30.6 The Kepler dichotomy

The over-abundance of single transiting systems is frequently referred to as *the Kepler dichotomy*. It suggests evidence for two separate populations of planetary systems: one where all orbits are confined to a single plane, and a second where the constituent planetary orbits possess significant mutual inclinations, such that only a single member is preferentially observed to transit. This in turn implies that the (Kepler) systems of small planets with  $P \lesssim 1$  yr, which exist around nearly half of all solar-type stars, are essentially as flat as the solar system.

Other evidence that single- and multi-transiting systems are qualitatively different is provided by the relative occurrence of detectable transit-timing variations (Xie et al., 2014); a (possibly related) sub-population of hot



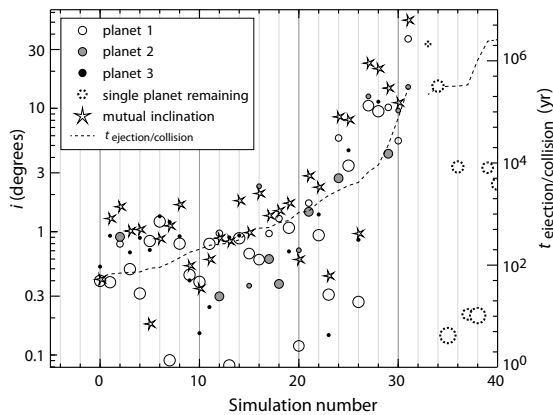


Figure 6.122: Orbit integrations of a Kepler-150-like system, with planets ‘mass boosted’ by  $\times 150$ . 40 simulations are sorted by instability time (typically, the middle planet collides with the inner, or all three merge). Symbol size is  $\propto R_p$ . Empty column 31 separates systems with 2 or 1 remaining planets. The plot shows  $\Delta i$  post-encounter (left axis), and the time-scale for the first ejection or collision (right axis, dashed curve). Resulting  $\Delta i$  are typically  $1 - 30^\circ$ , with  $e \sim 0.1$ . From Johansen et al. (2012, Figure 12c), by permission of IOP Publishing/AAS.

isolated Earth-size planets in the distribution of  $R_p$  versus  $P$  (Steffen & Coughlin, 2016); and various dynamical analyses, including possible effects of unseen companions (Becker & Adams, 2016, 2017; Hansen, 2017).

Ballard & Johnson (2016) found that the dichotomy holds for M dwarfs as well as solar-type stars.

**Possible explanations** On the hypothesis that planetary systems form with a range of masses, and that the most massive are inherently unstable to planet–planet interactions, Johansen et al. (2012) performed N-body simulations of ‘mass-boosted’ versions of the Kepler 3-planet templates finding that, typically, two planets collide and merge, leaving a moderately inclined 2-planet system (Figure 6.122). While this second population can, in principle, produce the large planets seen in single-transit systems, it does not explain an additional excess of small planets ( $< 4R_\oplus$ ) among the single-transit systems, nor the lack of gas giants in double-transit and triple-transit systems.

Their conclusion is that the main part of the dichotomy between systems showing single transits, and those showing double and triple transits, arose already during planet formation, when the migration or formation of a large planet suppressed the formation of additional planets in sub-au orbits.

The dichotomy could be resolved with a population of almost flat systems with one or more small planets within 0.5 au, combined with a population of inherently single systems with large planets. In this picture, the excess of large planets in single-transit systems may arise already at the planet formation stage, when the formation or migration of a massive gas giant in a system suppresses the formation of additional (small and large) planets (as proposed by Latham et al., 2011).

Such a mechanism has been proposed as inhibiting the growth of Mars during Jupiter’s period of inwards migration (Walsh et al., 2011), but may be even more effective in other systems where gas giants have migrated to sub-au orbits.

Moriarty & Ballard (2016) found that the dichotomy can

Table 6.4: Circumbinary planets discovered by Kepler.  $P_b$ ,  $e_b$  and  $P_p$ ,  $e_p$  are the binary and planet periods and eccentricities.

Name	$P_b$ (d)	$e_b$	$P_p$ (d)	$e_p$
Kepler-16	40.1	0.16	228.8	0.01
Kepler-34	28.0	0.52	288.8	0.18
Kepler-35	20.7	0.14	131.4	0.04
Kepler-38	18.8	0.10	106.0	0.07
Kepler-47 b	7.4	0.02	49.5	0.04
Kepler-47 c	"	"	303.1	$< 0.41$
Kepler-47 d	"	"	187.3	–
Kepler-64	20.0	0.21	138.5	0.07
Kepler-413	10.1	0.04	66.3	0.12
Kepler-453	27.3	0.05	240.5	0.04
Kepler-1647	11.3	0.16	1100	0.06

be explained by formation within planetesimal disks with varying surface density profiles. Their models predict a varying outcome dependent on stellar type: while the mode of planet formation that accounts for high multiplicity systems occurs in  $24 \pm 7\%$  of planetary systems orbiting GK stars, it occurs in  $63 \pm 16\%$  of planetary systems orbiting M dwarfs.

Spalding & Batygin (2016) demonstrated that stellar obliquity, excited within the disk-hosting stage, can also explain the dichotomy. In their model, young rapidly rotating stars generate a significant quadrupole moment, which torques the planetary orbits. The inner planets are influenced more strongly, exciting significant mutual inclinations, enhancing the number of single-transiting planets, sometimes through a dynamical instability. Furthermore, as hot stars appear to possess systematically higher obliquities, they suggested that single-transiting systems should be relatively more prevalent around more massive stars, and finding such a signature in the Kepler data.

Lai & Pu (2017) invoked the action of an external giant planet or stellar companion misaligned with the inner multi-planet system. The external companion excites mutual inclinations of the inner planets, causing such systems to appear as ‘Kepler singles’ in transit surveys.

Bovaird & Lineweaver (2017) suggested that the dichotomy is only required when the inner disks are assumed to be flared. For flat inner parts, they reproduced the observed planet multiplicity without invoking a dichotomy. Independent of the disk model assumed, they determined a mean number of about 2 planets per star for  $P = 3 - 200$  d and  $R_p = 1 - 5R_\oplus$ .

### 6.31 Circumbinary planets

An exoplanet orbiting an eclipsing binary star may manifest its presence both through an (irregular period) transit signal, sometimes referred to as a *tertiary eclipse* to distinguish it from the primary and secondary eclipses of the binary star (§6.3.3), along with variations in the primary and secondary eclipse times (§4.4).

No transiting circumbinary planets were found in a dedicated analysis of the 2000 eclipsing binaries observed by CoRoT (Klagyivik et al., 2017).

**Kepler discoveries** The Kepler circumbinary planets were discovered from quasi-periodic transit signatures, where departure from strictly periodic transits is caused by the binary motion (§6.3.3 and §6.12.3). Evidently,

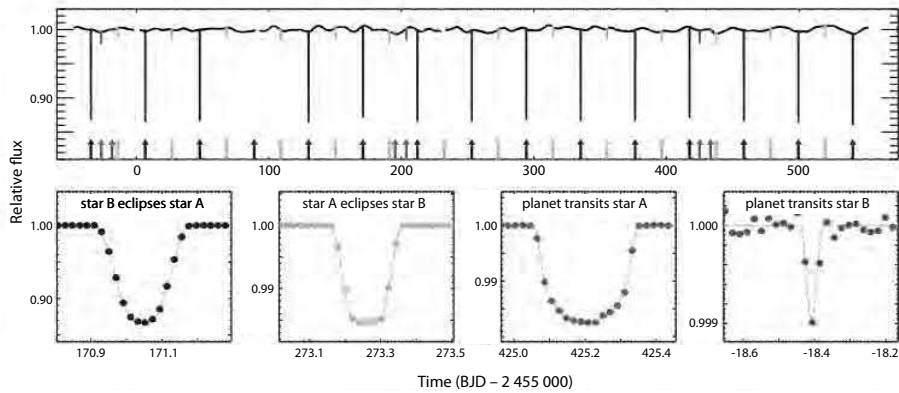


Figure 6.123: Top: photometric time series of Kepler-16 over 600 d. The various eclipses are identified as primary (star B eclipses star A), secondary (A occults B), tertiary (planet transits star A), and quaternary (planet transits star B). There is a changing order of the tertiary and quaternary eclipses due to the star's orbital motion (see original colour figure): the first and third pairs begin with the tertiary eclipse, whereas the second pair leads with the quaternary eclipse. Bottom: zooms of representative examples of each type of eclipse, along with the best-fit model. From Doyle et al. (2011, Figure 1), reprinted with permission from AAS.

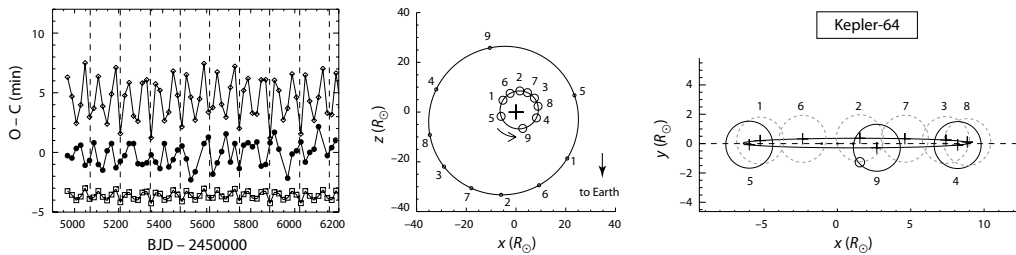


Figure 6.124: (a) Transit time variations for Kepler-64 showing the residuals ( $O-C$ ) as a function of time for a linear ephemeris (solid circles). The nine transit events are indicated by vertical dashed lines. Simulated  $O-C$  variations are also shown for a  $1M_J$  (lower curve, squares) and for a  $5M_J$  (upper curve, diamonds), each shifted vertically for clarity. Evidently, the circumbinary body's mass is less than  $5M_J$ . (b) Scaled face-on view of Kepler-64. Inner and outer ellipses show the primary and secondary orbits about the barycentre (+), with numbers indicating the configuration at the transit times. The planetary orbit is outside the scaled region. (c) Scaled schematic of Kepler-64. Positions of star A (large circles) are plotted at the 9 transit times (dashed circles indicate the far side of the orbit). Star B is shown to scale (small circle, arbitrarily positioned below star A at event 2). The planet also is shown to scale (smallest circles). From Kostov et al. (2013, Figures 6, 9, 10), by permission of IOP Publishing/AAS.

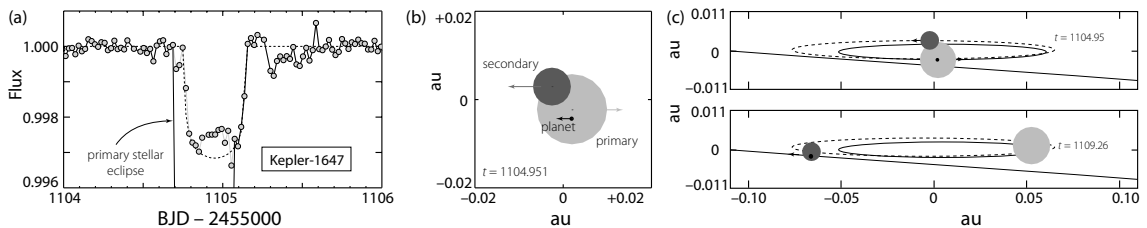


Figure 6.125: The circumbinary planet system Kepler-1647 at the time of the syzygy, shortly after a primary stellar eclipse. (a) Kepler long-cadence light-curve; grey circles and lines are after removal of a primary eclipse template; the dashed (and noisy) curve is the fit to the transit of the circumbinary planet across the primary star; (b) the configuration of the system at syzygy. Sizes of the objects are to scale, and arrows indicate their sky-projected direction of motion (the planet does not cross the disk of the secondary star); (c) ELC photo-dynamical solution for the orbit configuration at two consecutive circumbinary planet transits during the same conjunction for the planet. Orbits and stellar sizes are to scale, with the planet size increased by a factor 2. From Kostov et al. (2016b, Figures 10 and 13), by permission of IOP Publishing/AAS.

since most binaries do not eclipse, present searches for circumbinary planets are restricted to a very small fraction of the tens of thousands of binary stars within the Kepler field.

The first Kepler circumbinary discovery was Kepler-16. Subsequently, and as of the end of 2017, the mission has yielded 11 transiting circumbinary planets in 9 eclipsing binary systems: Kepler-16 (Doyle et al., 2011), Kepler-34 (Welsh et al., 2012), Kepler-35 (Welsh et al., 2012), Kepler-38 (Orosz et al., 2012b), Kepler-47 b,c,d (Orosz et al., 2012a; Kostov et al., 2013), Kepler-64 ( $\equiv$  PH-1, Schwamb et al., 2013; Kostov et al., 2013), Kepler-413 (Kostov et al., 2014), Kepler-453 (Welsh et al., 2015), and Kepler-1647 (Kostov et al., 2016b).

Just one hosts a multi-planet system, Kepler-47, with at least two planets, and a third currently unconfirmed.

The main orbital parameters of the Kepler circumbinary systems are summarised in Table 6.4, and some of the discoveries are described further below.

**System characterisation** Single-lined spectroscopic binaries do not normally allow for a full solution of the component masses. It is the precise times, durations and depths of the planetary transits and eclipses, along with light travel time effects, that allow strong constraints to be placed on the relative positions, velocities, sizes, and masses of the three bodies.

**Algorithmic implementation** These include:

**photodynam:** this allows the computation of observed fluxes in stellar and planetary systems with an arbitrary number of bodies that are part of a transit or occultation event (§6.14.16), and taking into account various limb-darkening models (Carter et al., 2011a; Pál, 2012).

**ELC:** originally described by Orosz & Hauschildt (2000, see also §6.13.2), and in particular its updated ‘photodynamical’ version described by Welsh et al. (2015). This allows for a dynamical modeling, instead of purely Keplerian kinematic modeling, by integrating the equations of motion under the assumption of point-masses and Newtonian gravity with general relativistic corrections.

**Individual Kepler systems** A number of systems provide excellent examples of precessional motion and resulting ‘transitional transits’ (§6.19.8).

**Kepler-16:** The first circumbinary planet discovered from the mission was Kepler-16(AB) b (Doyle et al., 2011). The system consists of a Saturn-mass planet on a circular orbit ( $P = 229$  d,  $e = 0.0069$ ) around an eccentric eclipsing binary ( $P = 41$  d,  $e = 0.16$ ). The light curve (Figure 6.123) shows primary eclipses (in which the larger star, A, is partially eclipsed by the smaller star B, and the flux drops by  $\sim 13\%$ ), secondary eclipses (in which B is completely occulted by A, with a flux decrease of 1.6%), tertiary eclipses of 1.7% depth as the planet transits star A, and 0.1% quaternary eclipses consistent with planetary transits across star B. The resulting 3-body induced eclipse timing variations yield  $M_p = 0.333 \pm 0.016 M_J$  and  $R_p = 0.7538 \pm 0.0025 R_J$ . The planet was predicted to cease transiting the secondary in 2014, to cease transiting the primary in 2018, and will

start to transit again in 2042 (Doyle et al., 2011). As of the end of 2017 there has been no confirmation of the cessation of secondary transits, while the latest model predicted cessation of primary transits on 2018 January 17 (Orosz, priv. comm.).

**Kepler-47:** is a 2/3-planet circumbinary system (Orosz et al., 2012a), and the first with evidence for more than one planet. Orosz et al. (2012a) also identified a single 0.2% deep transit not explicable by the two other transiting planets, and speculated that it could signify a third. Subsequent studies identified regions (in  $a$  and  $e$ ) of the 5-body phase-space where such a third planet could follow quasi-periodic orbits, stable over  $\sim 10$  Myr (Kratzer & Shannon, 2014; Hinse et al., 2015).

**Kepler-64:** An example of the associated transit time variations in the case of Kepler-64 is shown in Figure 6.124.

**Kepler-413:** is a transiting circumbinary planet orbiting a 10-d eclipsing binary in an eccentric orbit, with  $M_p = 4.3 R_{\oplus}$ ,  $P = 66$  d,  $a = 0.36$  au,  $e = 0.128$  (Kostov et al., 2014). The orbital plane of the eclipsing binary is slightly inclined to the line-of-sight ( $i = 87^\circ.3$ ), while the planet’s orbit plane is inclined by  $\sim 2^\circ.5$  to the binary plane at the reference epoch. Orbit precession with  $P \sim 11$  yr causes the (sky-projected) inclination of the planet to change continuously, leading to intervals of hundreds of days with no transits, and with the next occurring in 2020. Due to the eclipsing binary, the planet may experience Cassini state dynamics (§6.30.4), in which the planet’s obliquity precesses at a rate comparable to its orbit precession. Depending on its angular precession frequency, it could undergo obliquity fluctuations of tens of degrees as it precesses.

**Kepler-453:** The plane of the planet orbit is rapidly precessing, and its inclination only becomes sufficiently aligned with the primary star in the latter portion of the Kepler data. Thus three transits are present in the second half of the light curve, but none of the three conjunctions that occurred during the first half of the light curve produced observable transits. The precession period is  $\sim 10$  yr and, during that cycle, transits are visible for only 9% of the time. This implies that for every system like Kepler-453 detected, there are some 11 circumbinary systems that are not currently exhibiting transits.

**Kepler-1647:** The planet orbits an 11-d eclipsing binary comprising two  $1 M_{\odot}$  stars on a slightly inclined,  $e_p = 0.16$ , spin-synchronised orbit. It has a long orbital period (1100 d), and was at conjunction only twice during the mission. The planet produced three transits, one during an eclipse (Figure 6.125), creating a syzygy (§6.14.16). Measurable perturbations in the stellar eclipse times yield  $M_p = 1.52 \pm 0.65 M_J$ . The planet is in the system’s habitable zone (§11.7.1) throughout its orbit.

**Quadruple star systems** Two quadruple star transiting systems are known: Kepler-64 (PH-1), and 30 Ari. Both comprise two relatively close binary star pairs that are, themselves, widely separated.

**Tight transits** In a multi-planet single-star system, transit timing variations can occur, even in the absence of planet–planet interactions, simply due to the reflex motion of the inner binary (§6.20.2). An extreme analogue can occur in circumbinary systems, where a planet can transit the same star more than once during its orbit. This is referred to as *tight transits* by Liu et al. (2014b).

For simulated Kepler-16 analogues, and for certain architectures, Liu et al. (2014b) found very long transits and/or 2–3 transits during a single binary orbit, depend-

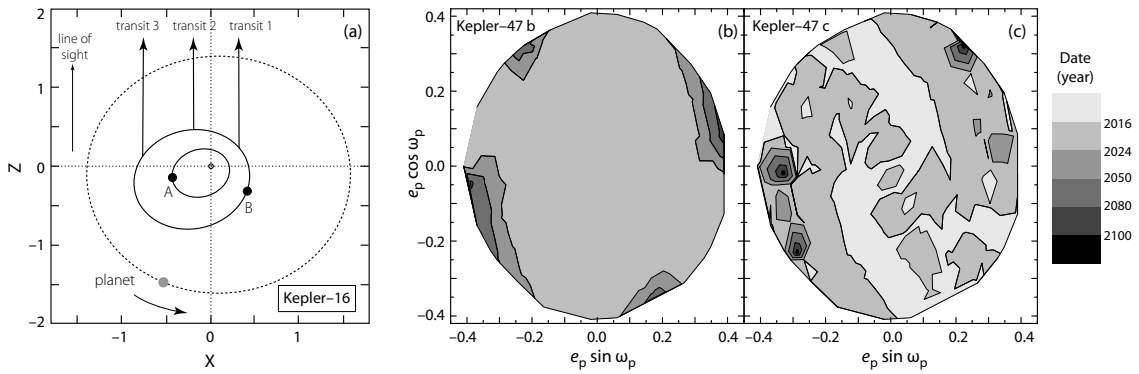


Figure 6.126: ‘Tight transits’, in which multiple transits of the same star can occur during one circumbinary orbit. (a) Kepler-16: arrows show the planet, and occulted star B, in three transits during the same orbit. (b,c) Kepler-47 b and c: in the full 4-body integrations,  $e_b$  and  $\omega_b$  are fixed to 0 (observationally,  $e_b < 0.035$ ).  $e_c \sin(\omega_c)$  and  $e_c \cos(\omega_c)$  are then varied over their range of possible values, subject to the observational constraint  $e_c < 0.411$ . Tight transits will typically occur between 2016–24 for Kepler-47 b, and possibly before 2016 for Kepler-47 c. From Liu et al. (2014b, Figures 1 and 5), by permission of IOP Publishing/AAS.

ing on the binary mass ratio (Figure 6.126a). They estimated that the effect can occur in half of known circumbinary systems. The earliest, for Kepler-47 b and c, is likely to occur before 2025 (Figure 6.126b,c).

**Insights into star and planet formation** Kepler insights into planet formation around binary and multiple stars are considered in the context of planet formation around binary systems more generally in Section 10.12.

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# Imaging

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IN THE CONTEXT OF current exoplanet research, imaging generally refers to the detection of a planet as a *point source* of light. This may, in principle, be either in the light reflected from the host star, or through the planet’s own thermal emission, and is to be distinguished from spatial resolution of an exoplanet surface. It is also distinguished here from the detection of an increased flux of the combined star–planet system as a result of (blended) light reflected from the planet, a decrease in intensity of the combined light as the planet enters a secondary eclipse, or a modified stellar spectrum in absorption or emission by a transiting planet, all of which are discussed in Chapter 6.

The first imaging detections, of massive, young, self-luminous, wide-orbit planets, were announced in 2005. By the end of 2017, the NASA Exoplanet Archive listed 44 discoveries, including planets in the well-studied debris disk systems  $\beta$  Pic and Fomalhaut, and two multi-planet systems, the 4-planet HR 8799 and the 2-planet LkCa 15. Multi-epoch observations reveal the orbital motion of the  $\beta$  Pic, HR 8799, and Fomalhaut planets.

State-of-the-art imaging instruments, designed and constructed in the past decade specifically with the goal of exoplanet imaging (including VLT–SPHERE, Gemini–GPI, and Subaru–HiCIAO) can still only directly image young, warm, and *self-luminous* giant planets. Detection of point source images of *reflected* starlight should be accessible to the planned 30–40-m telescopes, while Earth-like planet imaging still lies further in the future.

Imaging at X-ray and radio wavelengths is considered for star–planet interactions in Section 8.10.

## 7.1 Introduction

Exoplanet imaging represents a considerable technical challenge, both from ground and from space, because of the close proximity of planets to their host stars (in angular terms), and the very small ratio of the planet to stellar brightness (e.g. Claudi, 2016; Bowler, 2016).

A number of important objectives nevertheless motivates the challenging pursuit of exoplanet imaging.

These include: (a) gaining more direct confirmation of their existence; (b) discovering planets in wide orbits ( $a \geq 20$  au) that cannot easily be probed by other discovery techniques (because of their long dynamical time scales), and which provide unique constraints on theories of formation and evolution; (c) identifying and characterising orbital motion; (d) studying formation mechanisms and planet–disk interactions in young protoplanetary disks in which planet formation is ongoing; (e) as a precursor to more extensive spectroscopic investigations; and (f) as a first step towards a far-future goal of resolved spatial imaging of an exoplanet surface.

**Star–planet brightness** The ratio of the planet to stellar brightness depends on the stellar spectral type and luminosity class, the planet’s proximity to the star given by its orbital semi-major axis ( $a$ ) and instantaneous projected separation, on the planet’s mass, composition, radius ( $R_p$ ) and age, on the observation wavelength, and on the scattering properties of its atmosphere. For reflected light of wavelength  $\lambda$ , the planet/star flux ratio (or *fractional planet brightness*) can be written

$$\frac{f_p(\alpha, \lambda)}{f_\star(\lambda)} = p(\lambda) \left( \frac{R_p}{a} \right)^2 g(\alpha), \quad (7.1)$$

where  $p(\lambda)$  is the geometric albedo, and  $g(\alpha)$  is a phase-dependent function (§6.15.1). The formula, including the phase dependence, is modified if the planet’s thermal emission is significant.

The ratio  $f_p/f_\star$  is very small. For the Jupiter–Sun system, it is  $\sim 10^{-9}$  at maximum elongation, with  $\Delta\theta = 0.5$  arcsec at 10 pc. For the Earth–Sun system it is  $\sim 10^{-10}$ . Values for exoplanets likely range from  $10^{-5}$  in the infrared to  $10^{-10}$  in the optical (Figure 7.1).

**Angular separation** The star–planet angular separation,  $\Delta\theta$ , depends on the orbital parameters as well as on stellar distance. Exoplanets of interest typically lie very close in angular terms to the host star, within 0.1–0.5 arcsec, and swamped by the bright stellar glare. From a ground-based telescope, the planet signal is immersed within the star’s ‘seeing’ profile, of order 0.3–1 arcsec, arising from turbulent atmospheric refraction.

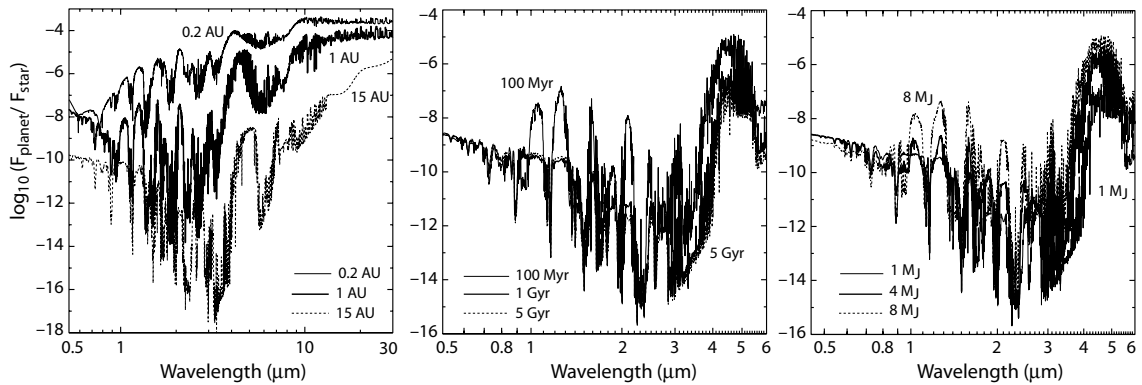


Figure 7.1: Predicted planet/star flux ratios versus wavelength. Models are for giant planets orbiting a G2V star of solar metallicity (phase-averaged,  $e = 0$ ,  $i = 0^\circ$ , effects of  $\text{H}_2\text{O}$  and  $\text{NH}_3$  clouds included): (a) for a  $1 M_J$  planet with an age of 5 Gyr as a function of  $a$ . The flux ratio is dominated by reflection in the optical (Rayleigh scattering and clouds), and by emission in the infrared; the transition occurs between  $0.8\text{--}3 \mu\text{m}$  depending on separation; (b) for a  $1 M_J$  planet at 4 au as a function of age; (c) for a 5 Gyr planet at 4 au as a function of  $M_p$ . From Burrows et al. (2004b, Figures 3, 6, 7), by permission of IOP Publishing/AAS.

Even when corrected using adaptive optics, or eliminated by observations from space, two further sources of light from the host star make direct exoplanet detection problematic: diffracted light from the telescope and supporting structures, and scattered light from wavefront aberrations, which result in a residual intensity in the focal plane in the form of instrumental *speckles*.

‘Speckles’ result from the interference of waves of the same frequency, having different phases and amplitudes, which add to give a resultant wave whose amplitude, and therefore intensity, varies randomly. In this context, they arise from both atmospheric phase fluctuations and instrument aberrations.

**Technical challenge** Under these conditions signal-to-noise calculations imply that obtaining a direct image of a planet is not feasible, and some means of removing or attenuating the star light is required to improve the signal-to-noise ratio at the position of the planet.

The technical challenges are considerable. Ground-based instruments targeting exoplanet imaging, for a favourable subset of star–planet properties and ages, have been under development for a number of years, and some major instruments have recently become operational. From space, ambitious plans for space interferometers and coronagraphs by NASA and ESA grew from an early phase of optimism in the late 1990s, but are currently not being pursued with the same urgency.

Observations in the infrared are facilitated by the simultaneous decrease in emission from the star and the increased thermal emission from the planet, and by the more technologically accessible implementation of adaptive optics at longer wavelengths. They are exacerbated, however, by decreasing diffraction-limited angular resolution, and technical complications of observing in the thermal infrared.

**Typical targets** While the first images of massive, widely-separated exoplanets have been acquired, none so far resemble those of the solar system. Indeed, the detection of exo-Earths remains out of reach of any of the facilities currently operational or under development (cf. Figure 7.21). Even the planned extremely large telescopes, or JWST in space, will continue to focus on:

(a) young stars (10–100 Myr,  $d < 100$  pc), around which the planets are still young, warm, and hence self-luminous. Evolutionary models predict exoplanet luminosities higher than for mature planets by several orders of magnitude depending on mass and age (Burrows et al., 1997; Chabrier et al., 2000; Burrows et al., 2004b);

(b) stars with known planets, for which the increasing temporal baseline of radial velocity surveys are identifying long-period trends suggestive of the existence of high-mass giant planets in wide-separation orbits;

(c) nearby stars,  $d < 5$  pc, in which a shorter-period giant planet with significant reflected light might be detected because of its relatively large angular separation from the star due to its proximity. For  $a = 0.05\text{--}1$  au, the flux ratio at  $20 \mu\text{m}$  can reach  $10^{-3}$  (Burrows et al., 2004b).

**Outline of techniques** Various techniques are being used to image exoplanets at high angular resolution and contrast (e.g. Absil & Mawet, 2010; Bowler, 2016). These include the use of large apertures to improve signal-to-noise ratio and resolution; adaptive optics to minimise effects of atmospheric turbulence, or imaging from space to eliminate its effects altogether; coronagraphic masking to suppress stellar light; post-processing to treat residual aberrations; interferometers to improve angular resolution, with nulling interferometry to eliminate the stellar light; and observations at longer wavelengths to improve the planet/star contrast.

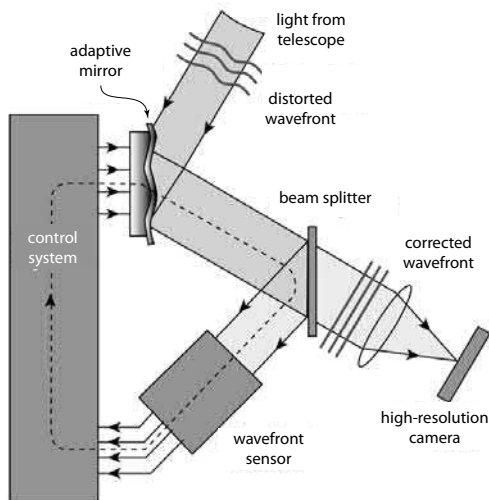


Figure 7.2: In adaptive optics, a wavefront distorted by the atmosphere is reflected from a deformable mirror with hundreds of actuators glued to its rear. The system operates in closed-loop, measuring the residual wavefront error after reflection using a wavefront sensor. Corrections are applied such as to leave the wavefront flat, updated thousands of times per second to match the rapidly changing effects of atmospheric turbulence. Courtesy: Claire Max, Center for Adaptive Optics, UCSC.

## 7.2 Active optics

Telescope mirrors were originally designed to retain their shape by virtue of their thickness and intrinsic stiffness, which limited maximum primary mirror diameters to around 5-m, as typified by the Palomar Observatory's Hale Telescope of 1949.

Since the demonstration of ESO's New Technology Telescope (NTT) in 1989 (Wilson, 1991), large telescopes have used thin-mirror technologies, in which the low-order figure of the primary is maintained through *active optics*. By monitoring image quality over time scales of seconds to minutes, coupled with an array of actuators operating to keep the mirror in an optimal shape, the effects of gravity, wind, and telescope alignment can be minimised (e.g., for LBT, see Hill, 2010).

The same principle of active mirror control is used in the replication of large apertures using multiple smaller segmented mirrors. It was used for the original MMT (e.g. Beckers et al., 1982), for telescopes such as Keck and HET, and will be used for the extremely large telescopes now under development (E-ELT, TMT, and GMT).

## 7.3 Atmospheric effects

A wavefront incident on a telescope pupil experiences phase and intensity fluctuations, both caused by refractive index variations in the turbulent atmosphere.

Phase fluctuations are responsible for atmospheric 'seeing' and image motion. This first-order effect (af-

fecting the wavefront angle) results from the integrated effect of light propagating through the atmosphere's full vertical depth, although it may be dominated in practice by the contributions from tolerably well-identifiable layers, both at high altitude as well as close to the ground. Rays are effectively redirected across the telescope pupil, resulting in a change in angle of the arriving wavefront, and degrading the image resolution.

The phase effects can be (partially) corrected using adaptive optics, while the techniques of 'speckle imaging' and 'lucky imaging' aim to recover some diffraction-limited information. The second-order (wavefront curvature) effect of 'scintillation', which mainly affects image intensity, and is therefore more relevant to transit photometry, is described separately (box, page 188).

### 7.3.1 Adaptive optics

Related to active optics, the more demanding technique of *adaptive optics* operates on shorter time scales of order 1 ms, and aims to compensate for atmospheric phase fluctuations across the telescope pupil to achieve diffraction-limited resolution ( $\lambda/D \approx 0.01$  arcsec at 500 nm for a 10-m telescope), using either a small corrective mirror or an adjustable secondary. Originally proposed by Babcock (1953), with first applications reported by Buffington et al. (1977), it has been under intensive development since the early 1990s (e.g. Golimowski et al., 1992; Beckers, 1993; Hubin & Noethe, 1993; Angel, 1994; Stahl & Sandler, 1995; Hardy, 1998; Wizinowich et al., 2000; Davies & Kasper, 2012).

In its basic form, measurement of the atmospheric phase fluctuations affecting a target star are made via the continuous measurement of the wavefront of a bright reference star nearby on the sky. An equal but opposite wavefront correction is then imposed using a deformable mirror containing voltage-responsive actuators distributed across its surface (Figure 7.2).

**Number of actuators** Wavefront sensing measurements, at frequencies of order 1 kHz, are made over pupil sub-apertures down to size  $\approx r_0$ , where the Fried parameter  $r_0$  is a measure of the coherence length of the atmospheric wavefront errors (Fried, 1965, 1966). Typical values at a good site are  $r_0 \sim 0.15 - 0.2$  m at visible wavelengths, increasing to  $\sim 1$  m at  $2 \mu\text{m}$ . Although the number of sensors and actuators required is ideally of order  $(D/r_0)^2$  (Angel, 1994), a significantly smaller number still produces images with a sharp core (Wang & Markey, 1978; Hardy, 1982; Roddier et al., 1991).

In the context of exoplanet imaging (§7.6), first-generation instruments employ  $\sim 200$  actuators, extreme adaptive optics systems of the second-generation employ  $\sim 40 \times 40$ , while systems with  $\sim 10^4$  are planned for the future ELTs (§7.6.3).

Adaptive optics systems cannot correct for atmospheric effects on spatial scales smaller than the interactuator spacing in the pupil plane. Power at higher spatial frequencies transforms into noise on large angular scales in the image plane. The final image therefore comprises a diffraction-limited core surrounded by an extended halo whose form reflects the number

of actuators, the characteristics of the atmospheric turbulence, and residual optical aberrations. Present adaptive optics systems nevertheless routinely deliver a *Strehl ratio*, the ratio of the peak intensity of the image to that of a perfect imaging system operating at the diffraction limit, of order 70%.

**Wavefront sensing** In practice, various wavefront-sensing schemes are in use: the Shack–Hartmann sensor measures the displacement of an array of sub-aperture images (e.g. Hardy, 1998; Rousset et al., 2003); the curvature sensor introduces a spherical phase aberration into the focal plane then transforms phase aberrations into light intensity modulations in the pupil plane (Roddier, 1988; Roddier et al., 1991); and the pyramid sensor divides the focal plane into four quadrants which are re-imaged in a separate pupil plane (Ragazzoni, 1996). Various comparative studies have been reported (e.g. Guyon, 2005; Véronaud et al., 2005), while new variants continue to be developed (e.g. Le Roux & Ragazzoni, 2005; Oti et al., 2005a; Butterley et al., 2006; Guyon et al., 2009; Guyon, 2010; Peter et al., 2010).

Stars bright enough to act as a natural wavefront reference must lie close to the observed source in angular terms, within the atmosphere's *isoplanatic patch* (over which the paths are temporally coherent):  $\lesssim 3$  arcsec in the visible, and  $\lesssim 30$  arcsec in the infrared. As one example of site characterisation, Masciadri et al. (2010b) give statistics for Mt Graham (LBT) covering seeing, wavefront coherence time, and isoplanatic angle.

**Laser guide stars** The fraction of sky with suitably bright natural guide stars is only of order a few per cent. The use of artificial laser guide stars was developed, in both the military and astronomical communities, as a way of extending the applicability of adaptive optics to arbitrary locations on the sky (e.g. Beckers, 1993; Hubin & Noethe, 1993; Lloyd-Hart et al., 1998; Ageorges & Dainty, 2000). The principle is to use a laser beam pulsed on the ground and reflected from the higher atmosphere, to mimic a bright artificial source of light subject to the same wavefront distortions.

Sodium beacon guide stars use (yellow) lasers tuned to the 589 nm Na D lines to excite non-ionised Na atoms naturally present in a  $\sim 5$  km thick mesospheric layer at an altitude of 80–100 km (Chapman, 1939). The fluorescing region appears as an artificial star at the targeted location. The mesospheric metal layer originates from the continuous ablation of meteors (e.g. Kane & Gardner, 1993); below it, Na is normally bound.

Rayleigh beacons use shorter wavelength (green) lasers, and rely on molecular Rayleigh scattering within the lower atmosphere, at altitudes of typically 10–15 km. Pulsed at  $\sim 10$  kHz, they can be time-gated to select the atmospheric layer at which the phase fluctuations are preferentially compensated.

**GLAO, MCAO, and XAO** In *ground-layer adaptive optics*, the goal is to correct the dominant boundary-layer turbulence over a wide field of order a few arcmin, improving the angular isoplanatism associated with single conjugated adaptive optics at the expense of diffraction-limited resolution (Rigaut et al., 2000; Hubin et al., 2005; Andersen et al., 2006).

In *multi-conjugate adaptive optics*, the goal is to increase the corrected field of view and reduce point-spread function variation over the field. Multiple wavefront sensors point at different locations, using several deformable mirrors optically conjugated at different altitudes to provide an optimum correction for the deformable mirrors (Goncharov et al., 2005; Vernet-Viard et al., 2005; Fusco et al., 2006a). These systems are being built into the designs of the new extremely large telescopes, both for the TMT (Gilles et al., 2006), and for the European–ELT (MAORY, Diolaiti et al., 2010).

In *extreme adaptive optics*, Strehl ratios  $\geq 90\%$  are targeted in the near infrared, using more sub-apertures ( $\sim 40 \times 40$ ) and higher control rates ( $\sim 2$  kHz). With coronagraphy and post processing, systems such as VLT–SPHERE and Gemini–GPI ( $\$7.6.2$ ) target contrast ratios of  $10^{-6} - 10^{-7}$  at 0.5 arcsec separation. The LBT ExAO system, equipped with the SHARK–VIS Forerunner, achieves a contrast of  $5 \times 10^{-5}$  at 630 nm beyond 0.1 arcsec (Pedichini et al., 2017).

**Operational systems** Routine use of laser guide star adaptive optics started at the Lick, Palomar and Keck observatories around 2006 (Wizinowich et al., 2006b), and at the VLT using NACO and SINFONI around 2007 (Rousset et al., 2003; Bonaccini Calia et al., 2003). Other systems are operational or under development at all large telescopes, including Subaru–AO188 with 188 actuators (Watanabe et al., 2004), Gemini–ALTAIR with 177 (Tracy et al., 2004; Lafrenière et al., 2008), and LBT–ARGOS with 672 (Rabien et al., 2008; Hill, 2010). ESO's Adaptive Optics Facility, with four laser guide stars and a thin deformable secondary, saw first light at UT4, with MUSE, in 2017 August (Bonaccini Calia et al., 2010; Arsenault et al., 2017).

### 7.3.2 Speckle and lucky imaging

The related techniques of 'speckle imaging' and 'lucky imaging' share the same goals as adaptive optics, which is to enhance ground-based telescope resolution in the presence of atmospheric phase fluctuations.

**Speckle imaging** Random atmospheric phase fluctuations, responsible for astronomical 'seeing', disrupt the single spot of a ground-based telescope's Airy disk into a pattern of similarly-sized constructive-interference spots scattered over a much larger area defining the 'seeing disk' (of order 1 arcsec). The high-resolution technique of *speckle imaging* exploits a large number of short exposures that freeze the variation of atmospheric turbulence, and allow a diffraction-limited image to be reconstructed, e.g. by image stacking or autocorrelation. As a consequence of the properties of atmospheric coherence, the technique requires short exposures (of order 100 ms in the infrared and 10 ms in the optical), and is limited to bright stars, to a field of typically 1–2 arcsec (within the isoplanatic patch), and to  $\Delta m \lesssim 3$  mag.

**Instruments** Enabled by advances in understanding atmospheric structure (Fried, 1966), the technique was pioneered in the 1970s (Labeurie, 1970), although it is now largely superseded by adaptive optics. The USNO speckle camera continued to make many observations of exoplanet host stars at the KPNO and CTIO 4-m telescopes from 2001–2010 (Mason et al., 2011). The Differential Speckle Survey Instrument (DSSI, Horch et al., 2008) has been used at the WIYN 3.5-m telescope since 2008 to provide diffraction-limited imaging of Kepler targets, and subsequently at the 8.1-m Gemini–North for a number of Kepler and CoRoT targets (Horch et al., 2012), a number of high-eccentricity planet host stars (Kane et al., 2014a), and various KELT planet hosts (Coker et al., 2017).

**Lucky imaging** Related to speckle imaging in its phenomenological basis, 'lucky imaging' is achieved by taking a sequence of images at frame rates 10–30 Hz (again,



dictated by the atmospheric coherence time) using a conventional but low-noise (electron-multiplying) high-speed CCD camera. Each short exposure suffers different atmospheric turbulence effects, resulting in rapid variations in image location and quality. Using the position of a bright object in the field to adjust its offset relative to some mean almost completely eliminates the tip-tilt distortions caused by atmospheric turbulence, and can improve median seeing at a typical observatory by a factor 2.5–3. This initial step forms the basis of the proposed GravityCam (Mackay et al., 2017).

The next level of disturbance of the wavefront entering the telescope is defocus. Using the same procedure, but now selecting and co-adding the best and sharpest images together is the method known as *lucky imaging* (Mackay et al., 2004). With a selection of the best half of the images, image resolution is improved to a total factor of 4. More demanding selection criteria can give still higher angular resolution at the expense of sensitivity (e.g. Baldwin et al., 2001a).

**Instruments** Operational instruments include the Cambridge Lucky Imaging system (LuckyCam), based on an (e2v) L3CCD with a 4 MHz pixel rate. At the 2.56-m NOT, near-diffraction limit performance in the I-band has been reported (Law et al., 2006). A system at Calar Alto, AstraLux, has been used to quantify multiplicity of exoplanet host stars (Hormuth et al., 2008; Ginski et al., 2012; Lillo-Box et al., 2014a; Ginski et al., 2016a).

Observations have been used to assess the multiplicity of Kepler (Lillo-Box et al., 2012) and other host stars (Ginski et al., 2012; Bergfors et al., 2013; Faedi et al., 2013b; Wöllert et al., 2015; Wöllert & Brandner, 2015).

Lucky imaging searches have been carried out with the Two Colour Instrument at the Danish 1.54-m telescope at ESO, by the MiNDSTeP consortium. Observations of 101 transiting planet hosts yielded 51 binary companions within 5 arcsec, and an overall multiplicity rate of 38% (Evans et al., 2016a).

## 7.4 Coronagraphic masks

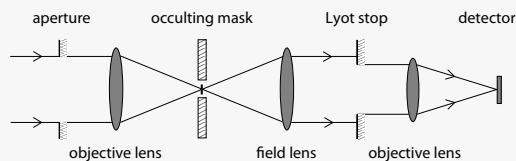
### 7.4.1 Introduction

For the reasons noted above, the point-spread function of a telescope equipped with adaptive optics typically consists of a bright diffraction-limited core, with several Airy rings superimposed on a wide scattered light halo containing several percent of the total flux. The improved image quality provides access to a region within a few times the telescope's diffraction width, with the dynamic range limited by the stellar halo and the bright Airy rings, rather than by atmospheric seeing.

Further significant enhancement in contrast can be achieved by suppressing the noise associated with the stellar light by rejecting it from the area of interest in the focal plane. The technique, employing some form of mask in the telescope focal plane, is referred to as *coronagraphy*, after its early development to observe the solar corona. The original Lyot coronagraph used an amplitude mask, physically blocking the central stel-

**The Lyot coronagraph for solar observation:** Coronagraphy was originally developed for studies of the solar corona outside periods of total eclipse, and included early attempts by Hale (1895). With the coronal brightness at 2 arcmin from the Sun's edge being a factor  $10^6$  less than that of the solar disk, the system had to overcome bright points of light diffracted by small bubbles in the glass, hollows and scratches on its surface, dust particles and, most severely, light diffracted by the edge of the lens.

The technical problems were considerable, and results were first achieved only in July 1931 from the Pic du Midi Observatory (Lyot, 1939). Glass free from inclusions, highly polished lenses, and a high altitude site to minimise atmospheric pollution were all essential.



In the Lyot coronagraph as implemented for observations of the solar corona, the first objective lens forms an image of the disk and corona, and an occulting mask blocks the image of the disk. If the occulting mask were the only blocking element, diffracted light would still swamp faint off-axis structure. Consequently, a field lens re-images the objective lens and its diffraction pattern, and the 'Lyot stop' intercepts the diffraction ring while allowing most of the light from surrounding structure to pass. The second objective lens relays the resulting image onto the detector plane. In a perfect Lyot coronagraph some 50% of the light from a nearby source might be lost, compared to the suppression of some 99% of the stellar light.

A similar sequence forms the basis of all coronagraphic concepts, with the occulting mask replaced by the relevant coronagraphic mask.

lar light, while more recent coronagraphs also employ phase masks to cancel light through self-interference.

As a result, the combination of a coronagraph with an adaptive optics system aims to block the core of the image of an on-axis point source, suppress the bright diffraction rings and halo, remove light that would otherwise reduce the dynamic range, and improve the prospects of imaging faint off-axis structure.

Coronagraphy without adaptive wave front correction, or with only low-order tip-tilt correction, has been used to access angular scales close to the central star and to prevent detector saturation (e.g. Golimowski et al., 1992; Nakajima et al., 1995), but is of limited relevance for exoplanet imaging from the ground where the very highest contrast ratios are now required.

Key performance metrics include throughput, the *inner working angle* (IWA), defined as the 50% off-axis throughput point and typically expressed in terms of  $\lambda/D$  (Mawet et al., 2012b), and the fraction of azimuthal space that may be simultaneously searched, which determines the coronagraph's efficiency.

Table 7.1: Coronagraphs theoretically able to achieve  $10^{10}$  contrast within  $5 \lambda/d$ , from Guyon et al. (2006b, Table 1). Designs post-dating that compilation, or of some other specific nature, are shown without abbreviation in column 2.

Coronagraph	Abbrev.	Reference
Interferometric coronagraphs:		
Achromatic interferometric coronagraph	AIC	Baudoz et al. (2000)
Common-path achromatic interferometer-coronagraph	CPAIC	Tavrov et al. (2005)
Visible nulling coronagraph, $x - y$ shear (fourth-order null)	VNC	Mennesson et al. (2003)
Pupil swapping coronagraph	PSC	Guyon & Shao (2006)
Achromatic rotation-shearing coronagraph	ARC	Aime et al. (2010)
Pupil apodisation:		
Conventional pupil apodisation and shaped-pupil	CPA	Debes et al. (2002), Kasdin et al. (2003)
Achromatic pupil phase apodisation	PPA	Yang & Kostinski (2004)
Phase-induced amplitude apodisation coronagraph	PIAAC	Guyon (2003), Guyon et al. (2005)
Phase-induced zonal Zernike apodisation	PIZZA	Martinache (2004)
Spiderweb/star-shaped mask	–	Vanderbei et al. (2003b), Vanderbei et al. (2003a)
Checkerboard mask	–	Vanderbei et al. (2004)
Improved Lyot concept with amplitude masks:		
Apodised pupil Lyot coronagraph	APLC	Soummer et al. (2003a,b)
Apodised pupil Lyot coronagraph, multi-stage ( $N$ steps)	APLCN	Aime & Soummer (2004)
Band limited, fourth-order	BL4	Kuchner & Traub (2002)
Band limited, eighth-order	BL8	Kuchner et al. (2005), Shaklan & Green (2005)
Band limited, notch-filter	–	Kuchner & Spergel (2003), Debes et al. (2004)
Achromatic prolate apodised Lyot coronagraph	–	Aime (2005)
Binary apodisation	–	Cady et al. (2009)
Improved Lyot concept with phase masks:		
Phase mask	PM	Roddier & Roddier (1997)
Four quadrant phase mask	4QPM	Rouan et al. (2000), Riaud et al. (2001)
Eight octant phase mask	–	Murakami et al. (2008)
Achromatic phase knife coronagraph	APKC	Abe et al. (2001)
Optical vortex coronagraph, with topological charge $m$	OVC $m$	Foo et al. (2005), Palacios (2005)
Annular groove phase mask coronagraph	AGPMC	Mawet et al. (2005)
Optical differentiation	ODC	Oti et al. (2005b)
Achromatic chessboard	–	Rouan & Pelat (2008)

**Lyot coronagraphs and adaptive optics** Ideally, a coronagraph coupled to an adaptive optics system would perform as if placed above the atmosphere. The image of a point source in the image plane would be a pure Airy disk, and the size of the Lyot stop could be chosen using Fourier theory. Malbet (1996) and Sivaramakrishnan et al. (2001) provide further details of the basic Lyot coronagraph combined with adaptive optics, with the latter demonstrating how the Lyot stop must be optimised for a given telescope according to atmospheric conditions.

Classical Lyot coronagraphs are used, for example, with Gemini South–NICI (Chun et al., 2008), Subaru–CIAO (Tamura et al., 2000), and with VLT–NACO, with a focal spot of 0.7 or 1.4 arcsec (Boccaletti et al., 2009). Application to segmented mirrors was evaluated by Sivaramakrishnan & Yaitskova (2005). Other comparisons have been made by Crepp et al. (2007).

For a perfect coronagraph, and an entrance pupil with no phase aberrations, there would be zero light outside of some specified angle. In practice, and as considered further in §7.4.5, two effects limit the efficiency of all coronagraphs in the imaging of exoplanets in which the host stars are point-like sources and the images are dominated by diffraction: residual effects due to imperfect atmospheric correction, and imperfect optics.

**Post-Lyot coronagraphs** Other concepts for high-rejection coronagraphs have been stimulated by the prospects of exoplanet imaging, and a large literature on optimised designs and laboratory tests has appeared in the last ten years (e.g. Ferrari et al., 2007; Guyon, 2007; Oppenheimer & Hinkley, 2009). New and optimised designs are still being discovered, some (notably the optical vortex coronagraph) exploiting new basic physics.

Coronagraphic surveys have been carried out with a number of ground-based telescopes, and coronagraphs have been built into space-based telescopes, notably HST and JWST. Designs include modified opaque disks to suppress the amplitude of the starlight, as in the original Lyot design, as well as systems which modify its phase to create self-destructive interference (Gay & Rabbia, 1996).

Results of an international meeting in 2004 with the goal of optimising coronagraphic designs for exoplanet detection, and in particular within the context of JWST and TPF–C, has been made available by Quirrenbach (2005). For some high-performance coronagraphs, the inner working angle is very sensitive to the source size (viz. to a finite stellar diameter), ruling them out for terrestrial planet imaging (Guyon et al., 2006b).

Polarisation dependencies are reviewed by Breckinridge & Oppenheimer (2004) and, in the context of nulling interferometry, Spronck & Pereira (2009). Laboratory evaluations are undertaken with facilities such as ESO’s High-Order Testbench, their adaptive optics facility which includes a turbulence generator as well as high-order adaptive optics (Martinez et al., 2011).

#### 7.4.2 Classification of concepts

From an optical design perspective, there are four main groups of coronagraphs: amplitude apodisation or phase apodisation in the *pupil plane*, and amplitude masking or phase masking in the *focal plane*. Classical Lyot coronagraphs are an example of amplitude masking in the focal plane.

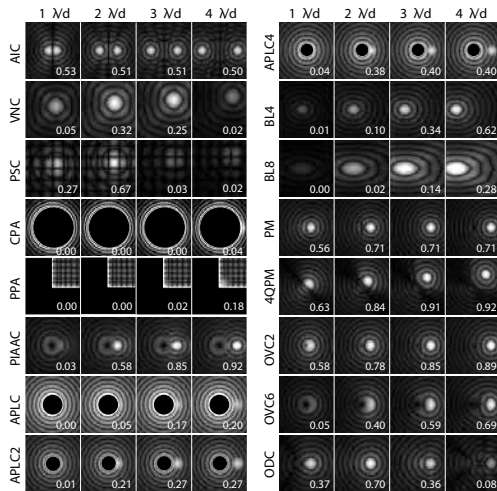


Figure 7.3: Simulated monochromatic point-source images of a  $10^{10}$  contrast system, at angular separations  $\lambda/d$  to  $4\lambda/d$ , for the coronagraphs in Table 7.1. The number in each image is the throughput for the off-axis source. The pixel scale is the same in all images, but the brightness scale is not. The companion is moving on a diagonal (rather than horizontal) line for VNC, PSC, PPA and 4QPM. From Guyon et al. (2006b, Figure 1), by permission of IOP Publishing/AAS.

Amplitude apodisation in the pupil plane can be further subdivided into coronagraphs employing intensity modification (or pupil shaping), and those employing phase-induced amplitude apodisation, in which the mirrors are warped to reshape the distribution of light in the pupil to yield an apodised shape (Mawet et al., 2009).

Along similar lines, Guyon et al. (2006b) divided existing coronagraph concepts into four categories, and made a synthesis of the performance of various designs relevant for unobstructed circular pupils, known to provide a theoretically achievable  $10^{10}$  point-spread function contrast within  $5\lambda/D$  of the central source. This synthesis is summarised in Table 7.1, and their performances are illustrated in Figures 7.3–7.4. Some of these concepts are known to provide very high attenuation, but only under specific conditions which are hardly achievable in practice. The literature includes various other implementations not detailed here.

The following is a summary of the four categories described by Guyon et al. (2006b). Two high-performance examples – the four-quadrant phase mask and the optical vortex coronagraph – are then detailed further.

**Interferometric coronagraphs** Akin to nulling interferometers, this class relies on interferometric combination of discrete beams derived from the entrance pupil. Examples include the *achromatic interferometric coronagraph*, which uses a beam splitter to destructively combine two copies of the entrance pupil, one of them  $\pi$ -phase shifted and flipped. The *common-path achromatic interferometric coronagraph* uses the same principles, with a common-path interferometer. The *visible-nulling coronagraph* is the coronagraphic equivalent of

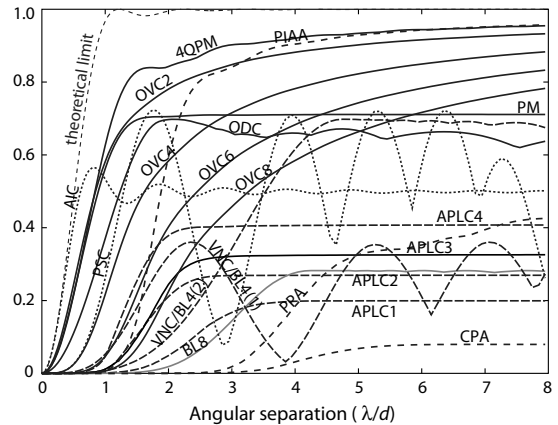


Figure 7.4: Throughput, at the  $10^{10}$  contrast level, of the coronagraphs listed in Table 7.1 as a function of angular separation, for a monochromatic point-like source. For coronagraphs with preferential directions (BLA, BL8, 4QPM, ODC, VNC, PSC), the peak throughput is shown, assuming that the telescope orientation is optimal. From Guyon et al. (2006b, Figure 3), by permission of IOP Publishing/AAS.

a double-Bracewell nulling interferometer, in which two successive shears in perpendicular directions produce four beams which, when combined, yield a fourth-order null in the pupil plane, thus combining a deep null with imaging capability. In the *pupil swapping coronagraph*, parts of the pupil are geometrically swapped prior to destructive interferometric combination, thus avoiding the throughput loss due to the shear in the visible-nulling coronagraph.

A variation of the interferometric coronagraphs, *pupil remapping*, divides the pupil into coherent sub-apertures, feeding each into a single-mode optical fiber, and remapping the exit pupil to allow non-redundant interference of all sub-apertures. A diffraction-limited image, with high dynamic range and free of speckle noise, is reconstructed from the fringe pattern (Perrin et al., 2006; Lacour et al., 2007; Kotani et al., 2009; Serabyn, 2009; Huby et al., 2013).

**Pupil apodisation coronagraphs** These designs are all characterised by a modification of the pupil complex amplitude (i.e. modifying the light transmission on the pupil), yielding a point-spread function suitable for high-contrast imaging. Apodisation can be performed by a pupil plane amplitude mask which can be continuous or binary, or by a phase mask.

The phase-induced amplitude apodisation coronagraph (Guyon et al., 2005) achieves an inner working angle of  $1.5\lambda/D$ , a radial field of  $100\lambda/D$ , and nominal detectability of an exo-Earth at 10 pc with a 4-m space telescope in 30 s. Developments continue to be reported (e.g. Guyon et al., 2010; Pueyo et al., 2011; Cady, 2012; Martinache et al., 2012a; Guyon et al., 2014; Haze et al., 2015). The same technique is also referred to as *pupil mapping* (Traub & Vanderbei, 2003; Vanderbei & Traub, 2005), and as *intrinsic apodisation* (Goncharov et al., 2002).

Active pupil apodisation using an (achromatic) liquid crystal array has also been proposed (Ren & Zhu, 2011; Dou et al., 2014; Liu et al., 2015d). Recent concepts, targeting a 12-m space coronagraph and a contrast, at 500 nm, of  $10^{10}$  at 34 mas, and therefore suitable for imaging exo-Earth candidates around nearby (5 pc) stars, are described by N'Diaye et al. (2016).

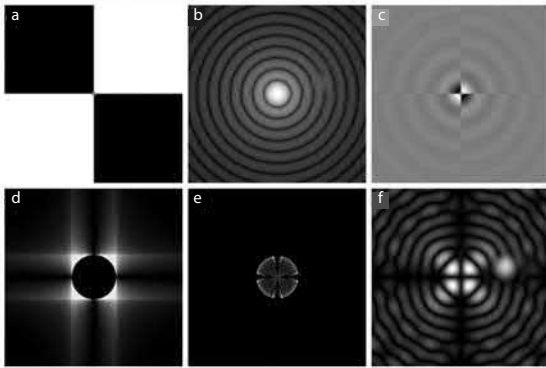


Figure 7.5: Simulation of the four-quadrant phase mask coronagraph and the detection of a companion 15 mag fainter at angular distance  $2.1\lambda/d$ : (a) the phase mask, with white/black for  $0/\pi$  phase shifts, which takes the place of the occulting mask in the Lyot design; (b) the Airy pattern; (c) the complex amplitude of the star phase-shifted by the mask; (d) the exit pupil; (e) the exit pupil viewed through the Lyot stop; (f) final coronagraphic image, with companion. From Rouan et al. (2000, Figure 2), reproduced by permission, Institute of Physics Publishing.

**Improved Lyot coronagraphs with amplitude masks** Improved performance of the basic Lyot design can be obtained by better matching the Lyot stop to the light distribution in the re-imaged pupil. This can be by adapting the pupil to the hard-edge of the focal plane mask using apodisation (non-uniform transmissivity), as in the *apodised pupil Lyot coronagraph*, or by adapting the mask to the telescope pupil by using *band-limited masks* in the focal plane.

Apodised Lyot masks are used for JWST–NIRCam, and Krist et al. (2007) illustrates how the corresponding Lyot stops are matched to the (segmented) telescope pupil pattern. Martinez et al. (2008) considered the apodised pupil Lyot coronagraph as a suitable baseline for the 30–40 m extremely large telescopes.

**Improved Lyot coronagraphs with phase masks** A phase mask can be used to introduce phase shifts in the focal plane to create self-destructive interference, rather than employing an opaque disk to block the stellar light. Examples include the *four-quadrant phase mask coronagraph*, the related *achromatic phase knife coronagraph*, and the *optical vortex coronagraph*, comprising both scalar and vector variants.

Unlike ‘Lyot family’ amplitude coronagraphs, these focal-plane phase masks provide a very small inner working angle, and two leading variants (the four-quadrant phase mask and the optical vortex coronagraph) are described in further detail below. Variants include the broad-band capabilities of dual-zone phase masks (Delorme et al., 2016).

**Four-quadrant phase mask** Figure 7.5 shows the successive steps in the image generation for the *four-quadrant phase mask* coronagraph (Rouan et al., 2000). This is based on the principle of a phase mask originally proposed by Roddier & Roddier (1997), but less sensitive to atmospheric turbulence and misalignment.

The focal plane is divided into four equal-area quadrants, centred on the optical axis. A  $\pi$  phase shift is applied to opposing quadrants, which results in destructive interference for a bright star located at its centre. A Lyot stop is placed in the exit pupil to

**Photon orbital angular momentum:** As described in the classical texts of Jackson (1998) and Mandel & Wolf (1995) electromagnetic radiation carries both energy and momentum. The angular momentum itself has two components: a spin component, more commonly referred to phenomenologically as polarisation, and measured mechanically by Beth (1936). The *spin angular momentum* takes two orthogonal values  $\pm\hbar$ , directed along the axis of propagation. Electromagnetic radiation also carries *orbital angular momentum*, associated with its spatial distribution, and consisting of an infinite number of orthogonal states.

Allen et al. (1992) showed that a Laguerre–Gaussian mode (i.e. a beam in which the transverse electric field and intensity distribution are Gaussian; and in which cylindrical symmetry yields a solution of the paraxial wave equation with an azimuthal dependence of  $\exp(-il\phi)$  where  $l$  is the azimuthal mode index) carries an orbital angular momentum of  $l\hbar$  per photon. This ‘twisted light’ phenomenon arises because the electric or magnetic vector has a forward-leaning component that spirals around the propagation axis – the greater the angular momentum, the larger the number of nested spiral windings. Curtis et al. (2002) already reported beams with  $l = 200$ .

Vortex phase masks to transform a planar into a helical wavefront, thus imparting orbital angular momentum, were originally developed in discrete steps by etching the phase ramp in a dielectric material such as fused silica. Nearly continuous helical surfaces can now be made out of liquid crystal polymers (Mawet et al., 2009). Conversely, such photons can be sorted using a cascade of Mach–Zehnder interferometers equipped with Dove prisms. It follows that a single photon can be encoded with  $\log_2 N$  bits of information (Vaziri et al., 2002), of interest in communications, and perhaps to SETI in view of the probable absence of naturally occurring photons with large  $l\hbar$ .

Other applications in physics are described by Padgett et al. (2004), while other astronomical applications are also receiving consideration (e.g. Harwit, 2003; Elias, 2008).

remove diffracted starlight, as in the original Lyot coronagraph. Implementation is based on the precision mounting of four half-wave plates (Riaud et al., 2003). In practice, implementation of the  $\pi$  phase shift tends to introduce chromatic terms, while the phase transitions between adjacent quadrants introduces large dead zones (Riaud et al., 2001). Chromatic dependencies in the coronagraph can be addressed through multi-stage monochromatic masks (Galicher et al., 2011a).

Such a mask has been used with VLT–NACO, providing central light attenuation  $\sim 10$  for long exposures (Boccaletti et al., 2004; Gratadour et al., 2005; Riaud et al., 2006). It is one of the coronagraphs used in VLT–SPHERE (Boccaletti et al., 2008a), and in JWST–MIRI (Baudoz et al., 2006).

**Optical vortex coronagraph** This high-performant class of phase mask is based on optical vortex spatial filtering (Khonina et al., 1992), itself based on the orbital angular momentum properties of light (Allen et al., 1992; Harwit, 2003, see box, page 336).

**Theoretical basis** The vortex phase mask, located at the focus of a circularly symmetric optical system, introduces a phase proportional to  $m\theta$ , where  $\theta$  is an azimuthal coordinate in the focal plane, and  $m$  is an integer called the winding number or

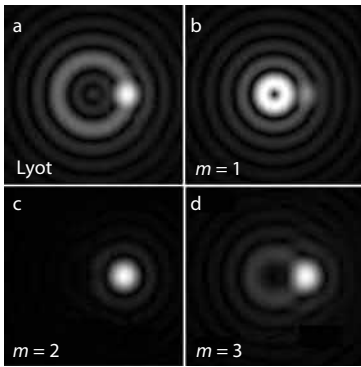


Figure 7.6: Simulation of the optical vortex coronagraph with star–planet intensity ratio 100, and the planet at the angular separation of the  $m = 1$  ring: (a) performance of the Lyot coronagraph; (b–d) performance of the optical vortex coronagraph with  $m = 1, 2, 3$  respectively. For  $m = 2$  the starlight is essentially eliminated. Adapted from Foo et al. (2005, Figure 3).

*topological charge* (Figure 7.7). This results in an *optical vortex* or phase singularity in the optical field, in which the intensity vanishes by total destructive interference. The resulting intensity profile of the diffracted vortex beam is characterised by a dark central core and annular rings (Figure 7.6). This dark core propagates and is conserved along the optical axis (Rozas et al., 1997; Niv et al., 2006).

For  $m = 2$ , for example, zero-intensity of the on-axis starlight results over the entire exit pupil, a phenomenon demonstrated analytically by Foo et al. (2005). For perfect optics, the vortex mask with a simple Lyot stop will therefore extinguish all light from an on-axis source.

More quantitatively, in cylindrical coordinates with the wave propagating along the  $z$  axis, the instantaneous electric field is described by (Foo et al., 2005, eqn 1)

$$E(r, \theta, z) = g(r, z) e^{im\phi} e^{-ikz}, \quad (7.2)$$

where  $g(r, z)$  is a circularly symmetric field amplitude about the beam axis,  $r = 0$ ,  $k = 2\pi/\lambda$  is the wavenumber, and the integer  $m$  is the topological charge. The resulting propagating wave consists of  $m$  intertwined helical wavefronts. All phases  $\phi$  appear along the beam axis, where destructive interference leads to zero intensity. Constructive interference occurs at a distance  $r_m$  off-axis, so that light brought to a focus forms a ring of radius (Harwit, 2003, eqn 6)

$$r_m = \frac{a\lambda f}{\pi\rho} \left(1 + \frac{m}{m_0}\right), \quad (7.3)$$

where  $f$  is the focal length,  $\rho$  is the radius of the optical train's effective aperture, and values of  $a \sim 2.585$  and  $m_0 \sim 9.80$  are determined experimentally (Curtis & Grier, 2003). The radius  $r_m$  is comparable to  $\lambda$ , and for small  $m$ , the ring is small compared to the Airy disk.

**Scalar and vector vortices** There are two kinds of optical vortices, and correspondingly two types of optical elements that induce them (Mawet et al., 2009).

The *scalar optical vortex* is based on a longitudinal phase delay (which applies to both polarisations identically), and is implemented via a structural helical phase ramp (Foo et al., 2005; Swartzlander et al., 2008). A broad-band variant, employing a pair of computer-generated phase gratings (one contain-

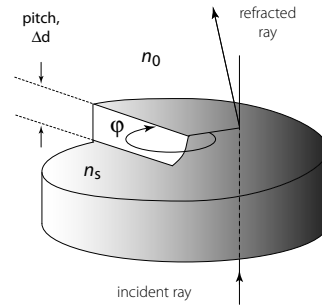


Figure 7.7: Schematic of a scalar vortex phase mask. The pitch of the substrate surface is  $\Delta d = m\lambda_0/(n_s - n_0)$  where  $\lambda_0$  is the design wavelength,  $m$  the topological charge, and  $n_s$  and  $n_0$  are the refractive index of substrate and superstrate (Swartzlander, 2006, eqn 3). For  $m = 2$  and an air–glass system with  $n_s - n_0 \sim 0.5$ ,  $\Delta d \sim 4\lambda_0$ . Adapted from Swartzlander (2006, Figure 1).

ing the optical singularity) to control the chromatic dispersion of the phase plates, is described by Errmann et al. (2013a).

The *vectorial optical vortex* is obtained by manipulating the transverse polarisation with birefringent elements (Riaud et al., 2012a). The phenomenon is based on the ‘geometric’ (or Pancharatnam–Berry) phase in classical and quantum mechanics, when both amplitude and phase are varied simultaneously (Berry, 1987).

Scalar vortex phase masks were originally made by etching the phase ramp in a dielectric material such as fused silica. Nearly continuous helical surfaces are now made with liquid crystal polymers (Mawet et al., 2009).

Vectorial vortex masks in the form of annular groove phase masks (AGPM, Figure 7.8) are fabricated by etching concentric sub-wavelength gratings onto diamond substrates (Mawet et al., 2005, 2013; Forsberg & Karlsson, 2013; Delacroix et al., 2013; Vargas Catalán et al., 2016). Birefringent liquid crystal polymers, oriented and hardened in a circular pattern, have also been used (Mawet et al., 2009).

**First exoplanet applications** The technique was proposed for exoplanet coronagraphy as an *optical vortex coronagraph* (OVC, Swartzlander, 2001; Foo et al., 2005) and, based on similar principles, as an *annular groove phase mask* (AGPM, Mawet et al., 2005), and as a *quantum coronagraphic mask* (Tamburini et al., 2006). It shows high performance (Guyon et al., 2006b), can be achromatic (Swartzlander, 2006), has small sensitivity to low-order aberrations (Palacios & Hunyadi, 2006), and performs respectably in the presence of central telescope obscuration and atmospheric turbulence (Jenkins, 2008). Observations are typically in the mid-infrared ( $L'$  band), where instrumental Strehl ratio, and planet/star brightness ratio, are both high.

Tests of a scalar mask (Swartzlander et al., 2008; Mawet et al., 2010) were followed by use with a 1.5-m sub-aperture of the Hale 5-m telescope (Serabyn et al., 2010), observing planets b–d known to orbit HR 8799 (Marois et al., 2008b), including the innermost planet at a separation of  $2\lambda/D$  (§7.10).

Laboratory tests of a (vectorial) mid-infrared (3–13  $\mu\text{m}$ ) annular groove phase mask showed excellent broad-band performance (Delacroix et al., 2013). Tests and first light at VLT–NACO and VLT–VISIR was reported in 2012 (Riaud et al., 2012b; Mawet et al., 2013). It yields a small inner working angle, down to  $0.9\lambda/D$  (0.09 arcsec in  $L'$  at the VLT), a  $360^\circ$  field out to 7.5 arcsec (set only by instrument constraints), and a high

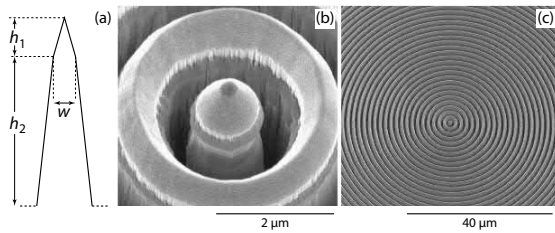


Figure 7.8: The VLT-NACO vectorial annular groove phase mask. (a) Profile schematic ( $h_1 = 1.0 \pm 0.1 \mu\text{m}$ ,  $h_2 = 5.0 \pm 0.1 \mu\text{m}$ ,  $w = 0.65 \pm 0.0.3 \mu\text{m}$ , grating pitch =  $1.42 \mu\text{m}$ ); (b–c) scanning electron microscope (SEM) images, showing (b) central zoom of the diamond mask, and (c) overall structure showing the uniformity and cleanliness. From Mawet et al. (2013, Figure 1), reproduced with permission © ESO.

achromatic throughput of 88%. Its raw contrast is  $\sim 2.5 \times 10^{-5}$  at  $2\lambda/D$ , more than needed for on-sky operations where the limit is set by residual wavefront aberrations. For integration times of a few hundred seconds, contrasts of  $\Delta L' > 7.5$  mag were demonstrated.

First light for a similar system for LBTI-LMIRCAM was reported in 2013 Defrère et al. (2014). An infrared vortex coronagraph for Keck-NIRC2 was installed in 2015, and has been used for observations of HIP 79124B (Serabyn et al., 2017), HD 141569A (Mawet et al., 2017a) and TW Hya (Ruane et al., 2017). An advanced mid-infrared vortex coronagraph for VLT-VISIR is under development as part of the ‘Breakthrough Watch’ programme (footnote, page 645).

A review of the development, commissioning, on-sky performance, and early scientific results of these new coronagraphic modes is given by Absil et al. (2016).

### 7.4.3 Discovery space

Factors such as the wavelength dependence of the inner working angle and contrast dependencies due to phase errors, the expected exoplanet radii and albedos, and the contribution of zodiacal and exozodiacal light (§7.5.3), can be taken into account in the optimisation of coronagraphic searches (Brown, 2005; Agol, 2007).

Figure 7.9 shows the fractional planet brightness,  $f_p/F_\star$ , as a function of star–planet angular separation for planets seen in reflected starlight throughout the habitable zones of known stars within 30 pc, assuming that planets are Earth-like in size and albedo (Turnbull et al., 2012). Similar estimates for stars within 30 pc have been made by Lyon & Clampin (2012), who considered various telescope diameters along with wavefront error requirements, and sensing and control times.

Various Monte Carlo or Bayesian tools have been developed to assess detection prospects in direct imaging surveys (e.g. Bonavita et al., 2013; Stark et al., 2014a).

### 7.4.4 Other considerations

**Pupil replication** A somewhat distinct technique for increasing contrast is *pupil replication*. This optically rearranges the incoming wavefront to decrease the image diameter of a star

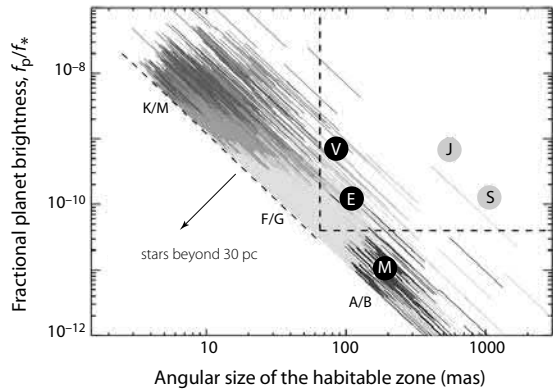


Figure 7.9: Fractional planet brightness,  $f_p/F_\star$ , versus star–planet angular separation for Earth-like planets in reflected light orbiting stars within 30 pc, assuming systems are pole-on (i.e., planets at quadrature). Lines cover the extent of the habitable zone for each star, and are on a grey scale representing spectral type. The dashed box shows detection limits for the proposed New Worlds Observer. Solar system planets are also shown for  $d = 10$  pc. From Turnbull et al. (2012, Figure 7), reproduced by permission, Institute of Physics Publishing.

on or very near to the optical axis, while preserving the angular position of an off-axis source (Greenaway et al., 2005).

The technique transforms the telescope into a pseudo-interferometer, and the field of view properties are analogous to those in pupil densification schemes (§7.8.2). Instrumental defects, such as surface errors and chromatic smearing, may limit the gains expected theoretically (Riaud et al., 2005; Spaan & Greenaway, 2007).

**Binary stars** Faint companions in binary star systems will typically not always be so easily detectable with conventional coronagraphic methods, although appropriate target selection will help (e.g. Thalmann et al., 2014a; Bonavita et al., 2016). For more problematic systems, Cady et al. (2011) proposed an apodised-pupil Lyot coronagraph with a pair of actively-controlled image-plane masks to suppress both stars simultaneously. Binary differential imaging (BDI), as a variant of angular differential imaging, with two stars imaged simultaneously (§7.4.5), has been attempted with MagAO-CLIO2.

**Long-slit spectroscopy** Specific challenges of coupling long-slit spectroscopy with coronagraphy, and a resulting apodised long-slit coronagraph, are described by Vigan et al. (2013).

**Segmented-mirror telescopes** High-contrast imaging with segmented (and/or on-axis) apertures faces the particular problem of large amplitude excursions in the telescope aperture due to secondary support structures and/or segment gaps. In this configuration, the deformable mirror surfaces that yield high-contrast point-spread functions is not linear. A corrective system comprising two sequential deformable mirror surfaces (Active Compensation of Aperture Discontinuities, ACAD) has been derived by Pueyo & Norman (2013).

**Free-flying occulters** A distinct coronagraphic implementation could be achieved, although with no confirmed plans yet to do so in practice, by placing an (external) occulting screen (or starshade) between star and telescope in the form of a suitably equipped free-flying satellite. Proposed concepts have included UMBRAS, designed around a 4-m telescope and a 10-m

occulter (Schultz et al., 2003), the much larger BOSS, the New Worlds Observer, and PlanetScope which places the free-flying coronagraph on a stratospheric balloon platform (Traub et al., 2008). In all cases, control of diffracted light is still paramount.

The BOSS (Big Occulting Steerable Satellite) concept comprised a large occulting mask, nominally a  $70 \times 70 \text{ m}^2$  transparent square, with a radially-dependent, circular transmission function inscribed (Copi & Starkman, 2000). It would be supported by a framework of inflatable or deployable struts, and aligned with a ground- or space-based telescope. In combination with JWST, for example, both would be in a Lissajous-type orbit around the Sun–Earth Lagrange point L2, with the mask steered to observe a selected object using a combination of solar sailing and ion or chemical propulsion. Attenuation of  $4 \times 10^{-5}$  of the stellar light is predicted at  $1 \mu\text{m}$ . Their simulations suggested that planets separated by 0.1–0.2 arcsec from the host star of 8 mag could be seen down to a relative intensity of  $1 \times 10^{-9}$ . For systems like the solar system, Earth and Venus would be visible to 5 pc, with Jupiter and Saturn to 20 pc.

The New Worlds Observer (Cash et al., 2005; Cash, 2006; Vanderbei et al., 2007; Cash, 2011; Turnbull et al., 2012) proposes an L2-based 50 m occulting starshade at 80 000 km from a 4-m telescope. The baseline architecture targets an inner working angle of 65 mas, and a fractional planet brightness  $f_p/f_\star = 4 \times 10^{-11}$  (Figure 7.9). The occulter could also be used in combination with a ground-based telescope (Janson, 2007).

The exoplanet imaging performance of JWST combined with an external occulter, orbiting at 70 000 km, has also been assessed (Brown & Soummer, 2010; Catanzarite & Shao, 2011a). Assumptions include an inner working angle of 85 mas, an achievable contrast of  $\Delta m < 26$  mag, 26 target stars, and 70 re-targeting manoeuvres.

Applied to solar observations, ESA's technology demonstrator, PROBA-3, is a dual-satellite formation-flying coronagraph with external occulter (separated by 150 m), scheduled for launch in 2019 (Zhukov, 2016).

A variant of the distant occulter uses a Fresnel lens (cf. §7.8.1), combined with coronagraphs and apodisation. In the Fresnel Diffractive Array Imager, an array of sub-apertures on one spacecraft focuses the first diffraction order onto a field telescope some km distant (Koechlin et al., 2005). A prototype for the ISS is under consideration (Roux & Koechlin, 2018).

**Lunar occultation** The use of the lunar limb as an external occulter for exoplanet detection was considered already by Elliot (1978), who proposed a space telescope in an orbit yielding a stationary lunar occultation of any star lasting two hours, using the black limb of the moon as an occulting edge. Richichi (2003) estimated that at 2.2 and  $3.6 \mu\text{m}$ , 8–10 m telescopes could detect companions 5–11 mag fainter at separations down to 0.01 arcsec. Although insufficient to detect hot Jupiters, further gains will come with the 30–40 m ELTs.

#### 7.4.5 Speckle noise

The contrast detection limit within the wings of the point-spread function in adaptive optics imaging, with or without coronagraphs, is determined by two contributions: photon noise, and *speckle noise*. In the presence of photon noise alone, a 30–100 m telescope could detect an exo-Earth around very nearby stars (Angel, 2003b; Hawarden et al., 2003). In reality, exoplanet detection limits are currently dictated by how well speckle noise can be suppressed or calibrated.

Speckle noise arises from the essentially random intensity pattern produced by the mutual interference of a set of wavefronts. The term is used to describe effects due to both rapid atmospheric phase fluctuations, which evolve on time scales of order 1–10 ms, and those due to instrumental imperfections, which evolve on a variety of intermediate to long time scales. Even extremely small drifts in the wavefront change the speckle intensity noticeably: for a speckle intensity  $10^{-5}$  of the host star intensity to be stable to within 1%, the corresponding spatial frequency would need to be stable to  $2.5 \times 10^{-6} \lambda$ , or 4 pm at  $1.6 \mu\text{m}$  (Guyon, 2005).

Speckle patterns arising from atmospheric fluctuations formed the basis of the short-exposure technique of *speckle interferometry* (Labeyrie, 1970). In the related *dark speckle* technique (Labeyrie, 1995; Boccaletti et al., 1998), rapid changes in optical path length due to the atmospheric turbulence are exploited, with the goal of detecting the planet in very short exposures ( $\sim 1$  ms) when, by chance, the star light interferes destructively at the planet location. Atmospheric speckles are strongly attenuated in adaptive optics imaging (and totally eliminated in space imaging), and this technique is accordingly now of only historical interest.

More relevant for exoplanet imaging, quasi-static speckles are seen in a star image observed through imperfect optics. At separations  $\geq 0.5$  arcsec, the main source of long-exposure adaptive optics speckles results from surface errors on the telescope mirrors and instrument optics, including coronagraphs. The resulting noise (which can be quantified in terms of a Taylor series expansion of the pupil wave-front error as first-, second-, or higher-order speckles), can be an order-of-magnitude larger than the residual photon noise (Racine et al., 1999; Marois et al., 2000; Perrin et al., 2003; Bloemhof, 2004; Ren & Wang, 2006; Soummer et al., 2007; Bloemhof, 2007; Marois et al., 2008a; Ren et al., 2012; Martinez et al., 2012, 2013).

Various methods are in use to reduce its effects, either through suppression, or through calibration. State-of-the-art stress-polishing of 'super-smooth' aspheric optical surfaces is part of this effort (Hugot et al., 2012).

**Speckle suppression** The technique of *speckle suppression* involves measuring residual wavefront errors in the coronagraph image plane using some form of post-coronagraph wavefront sensor, with a subsequent deformable mirror thereafter applying appropriate wavefront corrections. Various technical implementations have been proposed, and some have been developed as laboratory prototypes (Angel, 2003b; Bloemhof, 2003; Codona & Angel, 2004; Giv'one et al., 2005; Bordé & Traub, 2006; Vasisht et al., 2006; Trauger & Traub, 2007; Galicher et al., 2008; Sivaramakrishnan et al., 2008; Ren et al., 2012; Frazin, 2013; Dou & Ren, 2016).

Interferometric subtraction makes use of the fact that, unlike the light from the nearby companion, speckles arising from the central source are coherent with it, whether the speckles are evolving rapidly as on the ground, or are essentially stationary

as in space (Guyon, 2004; Galicher et al., 2008). Detection of a substellar companion exploiting these coherence properties of light, and using the Palomar Stellar Double Coronagraph, was reported by Bottom et al. (2017). Post-coronagraphic phase-shifted holographic suppression has also been proposed (Labeyrie & Le Coroller, 2004; Ricci et al., 2009).

Sivaramakrishnan et al. (2002) showed that the widely-cited technique of *speckle decorrelation*, introducing many independent realisations of additional phase error into a wave front during one speckle lifetime, thus changing the instantaneous speckle pattern, was not effective in reducing speckle noise. In contrast, the technique of *adaptive pupil masking*, with independently-controllable elements in the conjugate pupil plane randomly allowing or blocking light in various sub-apertures, can force the quasi-static speckles to become dynamic, resulting in enhanced visibility at the expense of longer exposure times, with  $\Delta m = 11$  mag at  $5\lambda/D$  (Osborn, 2012).

**Speckle calibration** An alternative to speckle suppression is *speckle calibration*, which aims to disentangle stellar speckles from the exoplanet signal using characteristics present in the planet light but not in the starlight, based on some spectral (Racine et al., 1999) or polarimetric (Kuhn et al., 2001; Tamura et al., 2006) signal. Various techniques are employed (e.g. Mawet et al., 2012b; N'Diaye et al., 2013, and references), and observations and post-processing techniques currently achieve suppression factors of 20 to several hundred at separations down to  $4.5\lambda/D$  (e.g. Marois et al., 2008a; Crepp et al., 2011):

*Angular differential imaging*, ADI, exploits the intrinsic field-of-view rotation of altitude/azimuth telescopes, by keeping the telescope pupil fixed on the science camera, and allowing the field-of-view to rotate slowly with time around the star, such that patterns associated with optical aberrations are cancelled (Marois et al., 2006; Lafrenière et al., 2007b; Vigan et al., 2010; Milli et al., 2012; Esposito et al., 2014b). Early limits of  $6M_J$  around GJ 450 were reported using MMT-Clio (Heinze et al., 2006), and quasi-Gaussian residuals were reported using Gemini-ALTAIR-NIRI (Marois et al., 2008a). The technique was used in the early imaging of the three companions around HR 8799 with Keck and Gemini (Marois et al., 2008b, §7.10), and has been used widely since. A development based on PCA and machine-learning, LLSG, was applied to VLT-NACO images of  $\beta$  Pic (Gomez Gonzalez et al., 2016). A pipeline based on parallel Fourier transforms, GRAPHIC, is available for the reduction of data from VLT-NACO, VLT-SPHERE, Gemini-NICI, and Subaru-SCEXAO (Hagelberg et al., 2016). *Roll subtraction*, also exploiting ADI, is baselined for coronagraphic observations with JWST-NIRCam (Krist et al., 2007).

*Binary differential imaging*, BDI (as distinct from DBI), as a variant of angular differential imaging, makes use of two stars imaged simultaneously within the same isoplanatic patch, and exploits the discovery space of binary stars. It has been used with MagAO-CLIO2 (Rodigas et al., 2015).

*Spectral differential imaging*, SDI, aims to suppress the speckle pattern by separating light from a strong absorption or emission feature, e.g.  $\text{CH}_4$ , from the stellar spectrum (Racine et al., 1999; Marois et al., 2000, 2004, 2005; Biller et al., 2006; Vigan et al., 2010; Maire et al., 2014a), typically exploiting the fact that cool ( $T_{\text{eff}} < 1200$  K) substellar objects have strong  $\text{CH}_4$  absorption longward of  $1.62\ \mu\text{m}$  (Burrows et al., 2001, 2003b).

*Dual-beam imaging*, DBI, or *simultaneous differential imaging*, makes use of two simultaneous images while exploiting such physical properties, while multiple-channel SDI exploits the same technique with integral field spectroscopy.

*Polarised differential imaging*, PDI, or *dual imaging polarimetry* exploits the fact that direct stellar light is essentially unpolarised whereas scattered light from dust grains from the disk surface is polarised. It has provided insights into the inner structure of circumstellar disks (e.g. Apai et al., 2004a; Quanz et al., 2011, 2012a, 2013b; Hashimoto et al., 2012; Garufi et al., 2013; Thalmann et al., 2015; Ohta et al., 2016). It can similarly be implemented in dual-beam imaging, with simultaneous imaging of the linear polarisation of the source along two orthogonal directions (e.g. Hinkley et al., 2009). With VLT-NACO this is provided by a Wollaston prism which splits the incoming light into ordinary and extraordinary beams, offset by  $3.5$  arcsec along the detector's vertical direction (e.g. Garufi et al., 2013).

*Reference star differential imaging*, RDI, is used in high-stability second-generation instruments where strong correlations exist between the target and reference stars (e.g. Serabyn et al., 2010; Mawet et al., 2010).

The VLT-NACO-SDI simultaneous differential imager (Lenzen et al., 2004), for example, provides four simultaneous images through three narrow-band filters, with two inside and two outside the  $1.6\ \mu\text{m}$   $\text{CH}_4$  features. The point-spread function, including residual aberrations and speckles, are largely identical. It was designed to search for  $\text{CH}_4$ -rich objects near to bright stars, with contrasts of 50 000. It was used to detect a companion at  $1.2$  arcsec from the star SCR 1845 (Biller et al., 2006).

Similar systems are implemented in MMT-ARIES-MEDI (Freed et al., 2003), CFHT-TRIDENT (Marois et al., 2005, 2008a), and Gemini South-NICI (Near-Infrared Coronagraphic Imager). NICI has 85-element adaptive optics, a Lyot coronagraph, and a dual-channel imager for spectral differential imaging which can also be used with angular differential imaging (Artigau et al., 2008; Chun et al., 2008). Other wavelength bands, e.g. [Fe II], may also be used (Tamura et al., 2006).

**Algorithmic implementation** Automatic recognition of an exoplanet in a speckle-dominated image, essentially by identifying structure on a given spatial scale, has been approached through various methods (see, e.g., Mawet et al. 2012b, Section 3.4; and for a comparison, see Savransky 2015). These include wavelet analysis (Masciadri & Raga, 2004), matched filtering and Bayesian techniques (Kasdin & Braems, 2006; Marsh et al., 2006; Ygouf et al., 2013), pre-whitening algorithms such as LOCI (Galicher et al., 2011b; Pueyo et al., 2012; Wahhaj et al., 2015) and ANDROMEDA (Cantalloube et al., 2015), and principal component analysis, such as PynPoint developed for differential imaging (Amara & Quanz, 2012; Amara et al., 2015), with KLIP (Hanson & Apai, 2015) and its forward modeling variant KLIP-FM developed and applied to GPI (Pueyo, 2016; Ruffio et al., 2017), VIP, a vortex image processing library, as applied to deep LBTI-LMIRCam imaging of HR 8799 (Gomez Gonzalez et al., 2017b), and PEX, Planet Extractor, based on a multi-spectral series expansion of the diffraction pattern, as applied to SPHERE/IFS (Devaney & Thiébaud, 2017)

As an example, KLIP (Karhunen-Loève Image Processing) is a principal component-type algorithm which operates from a library of PSF eigenimages containing all of the time-independent PSF sources that rotate with the field of view. KLIP then recreates any target from the input images as a superposition of library eigenimages, which is then subtracted from the original to reveal possible planetary candidates.

**Automation and machine learning** Paralleling the progress made in 'supervised learning' algorithms being applied to transit light curves (§6.12.3), similar techniques are being developed for image processing and object detection. As noted



above, a development based on principal component analysis and machine-learning, LLSG, was applied to VLT-NACO images of  $\beta$  Pic (Gomez Gonzalez et al., 2016). Further application of supervised learning to angular differential imaging sequences, with algorithmic solutions using the discriminative models SODIRF (a ‘random forest’ model) and SODINN (neural networks), are described by Gomez Gonzalez et al. (2017a).

**Other approaches** Other approaches to high-contrast imaging have been proposed. Galicher et al. (2010b) considered a self-coherent camera used as a focal-plane wavefront sensor for active correction and differential imaging. Based on light incoherence between the host star and its environment, the stellar speckles are spatially encoded in the science image so that differential aberrations are minimised.

At high-Strehl ratios, there are observables, in principle available from space-based imaging and adaptive optics imaging from the ground, which are immune to phase noise. Analogous to closure phase, they are referred to as *kernel phases* after their role in linear algebra (Martinache, 2010, 2012). Kernel phase reconstruction has been used to detect a known companion at a separation below the diffraction limit in archival HST-NICMOS data of GJ 164 (Martinache, 2010).

Speckle suppression using four space telescopes, discrete baseline coverage, and phase chopping, may allow the detection of an Earth analogue around a Sun-like star at 10 pc, with spectroscopy at  $R \sim 100$  over 8–19  $\mu\text{m}$  (Matsuo et al., 2011).

**Imaging combined with spectroscopy** High-contrast imaging combined with high-dispersion spectroscopy, variously termed spectroscopic coronagraphy or high-dispersion coronagraphy, can combine the contrast limits of imaging, limited by residual speckles, with those of spectroscopy, limited by stellar noise (Sparks & Ford, 2002; Kawahara & Hirano, 2014; Kawahara et al., 2014; Snellen et al., 2015; Wang et al., 2017c; Mawet et al., 2017b). The technique was first demonstrated in the determination of the spin-rotation of  $\beta$  Pic b (S2.5.4).

Simulations for E-ELT-METIS indicate that one night of observations at 4.8  $\mu\text{m}$  could detect a planet orbiting  $\alpha$  Cen A ( $R = 1.5R_{\oplus}$ ,  $T_{\text{eq}} = 300$  K) at a S/N of 5, while optical reflected light from an Earth-size planet in the habitable zone of Proxima Cen could be detected at a S/N of 10 (Snellen et al., 2015). Simulations for a Keck-based high-dispersion coronagraphy system are given by Wang et al. (2017c), who conclude that a ground-based system could detect an Earth-like planet in the habitable zone around an M dwarf.

## 7.5 Other considerations

### 7.5.1 Integral field spectroscopy

The term ‘3d spectroscopy’ embraces a number of techniques that produce spatially-resolved spectra over a 2d field. *Integral field spectroscopy* is a subset which acquires spectral and spatial data in one exposure. This contrasts with Fabry–Pérot interferometry and imaging Fourier transform spectroscopy which step temporally through wavelength space (or its Fourier conjugate),

leaving them more sensitive to changes in instrumental or sky background, albeit with a wider field for a given detector format.

Integral field spectroscopy was developed in the 1980s (e.g. Vanderriest, 1980; Bacon et al., 1995), and has since been used extensively for mapping velocity structures in external galaxies. Allington-Smith (2006) reviewed the optical designs used to access the spatially-resolved spectra (amongst them lenslet arrays, fiber arrays, and image slicers), and their expected role in the era of extremely large telescopes.

The technique was first applied to exoplanet host star spectroscopy for the transiting systems HD 209458 and HD 189733 using VLT-SINFONI (Angerhausen et al., 2006), WHT-INTEGRAL (Arribas et al., 2007), and Keck-OISIRIS (Angerhausen et al., 2009).

**Instruments and processing** Integral field spectroscopy is now incorporated into all second-generation exoplanet imaging instruments, including Palomar–Project 1640, VLT-SPHERE, Gemini–GPI, and Subaru–CHARIS (§7.6.2). One long-term goal is to facilitate the spectroscopic characterisation of exoplanets, while at the same time assisting in the distinction between exoplanets and artefact speckles (e.g. Sparks & Ford, 2002; Berton et al., 2006a,c; Vigan et al., 2007, 2008; Antichi et al., 2009; Greco & Brandt, 2016).

The processing and PSF calibration of the resulting 10000 or so closely-packed data cube is challenging. In *spectral deconvolution* (Sparks & Ford, 2002), extraction of the planetary spectrum within the multiple spectra is based on pattern recognition, aided by the time-varying velocity of the orbiting planet. Other implementations include the Project 1640 Data Cube Extraction Pipeline, PCXP (Zimmerman et al., 2011), and the Locally Optimised Combination of Images, LOCI (Galicher et al., 2011b; Pueyo et al., 2012; Wahhaj et al., 2015).

### 7.5.2 Astrometric orbits

**Determination** Once a faint object has been detected nearby to a star, further information is required to determine whether the two are gravitationally bound, or simply a chance alignment. Multi-epoch measurements can demonstrate whether the two are comoving, i.e. sharing the same proper motion and, by inference, the same space motion. Small additional relative image shifts may signify true orbital motion (e.g. Ginski et al., 2014).

Blunt et al. (2017) describe an algorithm, OFTI (for ‘Orbits for the Impatient’, using Bayesian rejection sampling) to compute posterior distributions of orbit elements for data covering short fractions of long-period orbits. They applied it to existing astrometry of 51 Eri b, and other long-period planets and brown dwarfs observed over less than 3% of their orbits.

Lannier et al. (2017) describe MESS2, a Monte Carlo simulation code, based on the generation of synthetic planet populations, combining radial velocity and direct imaging data obtained at different epochs to estimate the detection probability of giant planets spanning a range of physical separations.

**Zodi, the unit of exozodiacal dust:** The amount of dust in a debris disk is usually expressed in terms of the system's fractional dust luminosity,  $L_{\text{dust}}/L_{\star}$ , which relates the light absorbed by the dust and reemitted at thermal (infrared to mm) wavelengths relative to that from the star. This parameter, also called the *fractional infrared luminosity*, is determined by integrating the total long-wavelength excess flux in the disk's spectral energy distribution. It can be measured from unresolved photometry, and more easily at longer wavelengths where the stellar emission is relatively faint.  $L_{\text{dust}}/L_{\star}$  is not a unit of optical depth, dust mass, or surface brightness. In the optically thin case, it is proportional to the dust mass but is affected by grain properties such as size and composition (Shao et al., 2010).

In the context of direct exo-Earth observations, the quantity of debris dust in their habitable zones is typically given in units of *zodis*, intended as a convenient measure in terms of the solar system zodiacal dust.

Slightly different definitions are used: Gaidos (1999) defined one zodi as the effective emitting area of the solar system's zodiacal dust. Roberge & Kamp (2010) defined it as the fractional dust luminosity of the zodiacal dust,  $L_{\text{dust}}/L_{\star} \sim 10^{-7}$  (Nesvorný et al., 2010). With this measure,  $\beta$  Pic has some 10 000 zodis of cold dust. Millan-Gabet et al. (2011) take one zodi to signify a disk identical to the solar system's zodiacal dust in all respects, including total mass, spatial distribution, grain size distribution, albedo, and scattering phase function. Roberge et al. (2012) refer to such a disk as a zodiacal-twin disk.

**Scheduling** For a planet imaged in *reflected* light, the apparent brightness depends on the planet's orbital phase (§6.15.1). The planet may be unobservable, for example, even when outside the inner working angle, if the illuminated side of the planet faces away from Earth. Accordingly, a single image cannot distinguish between (say) Earth or Neptune mass, or determine if the planet lies in the habitable zone, or whether the image is a blend of multiple planets, perhaps leading to biased estimates of the orbital eccentricity (Pearce et al., 2014). Eccentricity further affects the epochs of favourable elongation. The availability of detailed astrometric orbits will allow such issues of scheduling and interpretation to be addressed (Shao et al., 2010; Janson, 2010; Catanzarite & Shao, 2011a; Davidson, 2011; Kane, 2013; Sozzetti et al., 2014).

**Orbital motion** A planet's 'intra-observation' orbital motion may no longer be negligible when using the future Extremely Large Telescopes to observe nearby stars (1–10 pc) over the long exposure times (10–20 h) necessary for direct detection of older planets in their habitable zone, perhaps limiting the achievable signal-to-noise ratio (Males et al., 2013).

### 7.5.3 Exozodiacal dust

Extended dust emission can be a pointer to ongoing planet formation (as in transition disks, §10.3.8), or ongoing collisional attrition in more evolved systems (as in debris disks, §10.6), although it can also be a barrier or complication to exoplanet detection in young systems.

In the solar system, *zodiacal dust*, recognisable through the reflection of sunlight as *zodiacal light*, is an important constituent of the Sun's debris disk (§12.5.13). By analogy, debris disk dust in exoplanet systems is referred to as *exozodiacal dust*, and quantified in terms of the comparative unit, the *zodi* (box, page 342).

**Occurrence and substructure** The occurrence and origin of debris disk dust is detailed in Section 10.6. When observed with high-contrast imaging in scattered (and polarised) light, debris disks often display structures such as narrow rings (e.g. HR 4796A; Schneider et al., 2009a; Lisse et al., 2017; Milli et al., 2017b), clumps (e.g.  $\epsilon$  Eri, Greaves et al., 2005), warps (e.g.  $\beta$  Pic, Currie et al., 2011b) or inclined sub-disks (e.g. AU Mic, Krist et al., 2005). Such structures are broadly attributed to a planet's dynamical influence, as are the clumps of zodiacal dust leading and trailing the Earth (§12.5.13).

**Effects on planet detection** The background flux from both local (solar system) zodiacal dust and the exozodiacal dust will likely dominate the signal of an Earth-analogue exoplanet in direct images and spectra, even if exozodiacal levels are no greater than that of the solar system, and will complicate direct imaging of exoplanets both as a source of noise, and as a source of confusion (Roberge et al., 2012; Kennedy & Piette, 2015).

Dust clumps may be a dominant source of confusion in direct imaging of Earth-like planets, since dynamical clumps will orbit the star, though not necessarily with the same period as the perturbing planet (Kuchner & Holman, 2003). Along with the fraction of potentially habitable planets ( $\eta_{\oplus}$ , §11.7.4), exozodiacal dust around nearby stars will therefore be relevant to the success of finding and characterising Earth-like planets.

For NASA's Exoplanet Exploration Program Analysis Group (ExoPAG), Roberge et al. (2012) assessed the impact of exozodiacal dust on high-contrast imaging, presenting the sensitivity of various facilities to thermal emission from debris dust around nearby solar-type stars (Figure 7.10). Recent results from the HOSTS survey of 30 stars are given by Ertel et al. (2018).

At optical wavelengths, dust migrating inwards from the cold outer regions of debris belts via Poynting–Robertson drag beyond 5 au, would be invisible to infrared surveys but another source of obscuration, termed *pseudo-zodiacal*, if observed edge-on (Stark et al., 2015).

## 7.6 Ground-based imaging instruments

**Classification** Mawet et al. (2012b) classified ongoing and planned imaging instruments into *first-generation* adaptive optics systems (including VLT–NACO, Keck–NIRC2, Palomar–WCS and HST–ACS); *second-generation* imaging instruments with extreme adaptive optics and high-performant coronagraphs (such as Gemini–GPI and VLT–SPHERE); and future *third-generation* instruments, including the space-based JWST–NIRCam, and ELT instruments such as TMT–PFI and E–ELT–EPICS.

Even third-generation systems will not achieve one of the key goals of planetary system studies, which is to find planets similar to Earth, perhaps pointing to 'habitable worlds' capable of supporting life. Only space op-

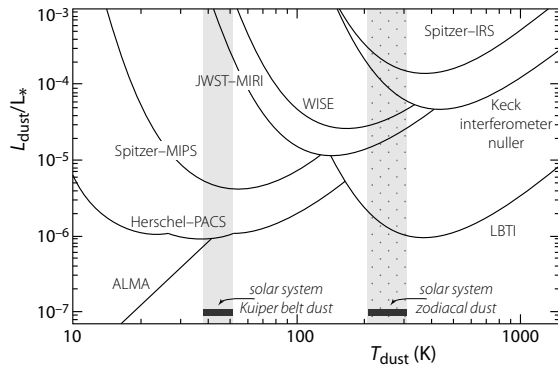


Figure 7.10: Instrument sensitivity limits ( $3\sigma$ ) for debris dust detection around nearby Sun-like stars in terms of  $L_{\text{dust}}/L_{\star}$  versus temperature. Ranges for dust in two zones around the Sun are shown as vertical bars: the Kuiper belt (30–55 au, grey), and the habitable zone (0.8–1.8 au, stippled).  $L_{\text{dust}}/L_{\star}$  for the solar system’s Kuiper belt dust,  $\sim 10^{-7}$  (Vitense et al., 2012), and zodiacal dust,  $\sim 10^{-7}$  (Nesvorný et al., 2010), are shown as horizontal shaded bars. Early results suggest that LBTI is slightly less sensitive than shown (Ertel et al., 2018). From Roberge et al. (2012, Figure 3), by permission, IOP Publishing.

tions such as nulling interferometry in the mid-infrared with a 30-m baseline space interferometer, or visible light coronagraphy with a 4–8 m space telescope, discussed in Section 7.7.3, are presently considered capable of imaging Earth-like planets even around nearby stars.

### 7.6.1 First-generation instruments

These include the first adaptive optics survey instruments at ground-based telescopes, as well as the space-based HST-ACS. High productivity instruments in this category include VLT-NACO (for NAOS-CONICA, themselves acronyms for Nasmyth Adaptive Optics System and Coudé Near Infrared Camera respectively), the VLT adaptive optics facility at UT1, which includes spectroscopic, polarimetric and coronagraphic capabilities (Girard et al., 2010), Keck-NIRC2 (McLean & Sprayberry, 2003), and Palomar-WCS, for Well-Corrected Subaperture (Serabyn et al., 2007).

In the absence of extreme adaptive optics or high-performant coronagraphs, their search space was largely restricted to stellar companions and massive young luminous exoplanets, typically on wide-orbits,  $a \gtrsim 25$  au. More recently, Keck-NIRC2 has been equipped with an infrared vortex coronagraph, and used for observations of HIP 79124B (Serabyn et al., 2017), HD 141569A (Mawet et al., 2017a) and TW Hya (Ruane et al., 2017).

### 7.6.2 Second-generation instruments

Two major instruments at 8-m telescopes have been developed specifically for exoplanet detection and characterisation, and became operational around 2015: SPHERE at the VLT, and GPI at Gemini South. Both have

dedicated extreme adaptive optics, employing of order 2000 actuators, and targeting Strehl ratios of 90% in the K-band. Both employ optimised coronagraphs, and are described here in further detail.

In addition, (a) Palomar-Project 1640 is a high-contrast imager with high-order adaptive optics, a  $66 \times 66$  deformable mirror (PALM-3000, Hinkley et al., 2011b; Roberts et al., 2012; Dekany et al., 2013), an apodised Lyot coronagraph, and integral field spectrograph (Hinkley et al., 2011b; Crepp et al., 2011; Zimmerman et al., 2011; Oppenheimer et al., 2012), (b) Subaru-HiCIAO is being upgraded to include a high-contrast near-infrared integral field spectrograph (CHARIS), (c) LBT has achieved first light with an L'-band AGPM vector vortex coronagraph (Defrère et al., 2014), and (d) Magellan-MagAO/Clio2 has achieved first light with a vector apodising phase plate coronagraph operating over 2–5  $\mu\text{m}$  (Otten et al., 2017).

**VLT-SPHERE** SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research; Beuzit et al., 2008) is a second-generation VLT imaging instrument, aiming for an order-of-magnitude improvement over NACO. It is optimised to provide the highest image quality and contrast in a narrow field of view around bright targets that are observed in the visible or near infrared. It is installed at the (stationary) Nasmyth focus of the VLT UT3, exploiting its stability through temperature and vibration control. First light was in June 2014. An overview of results is given in Section 7.9.

**Science goals** The SPHERE survey, over several hundred nights, includes nearby young associations, young active FK dwarfs, stars within 20 pc, and stars with known planets. It covers both young and evolved planetary systems, the former through their intrinsic infrared emission using differential imaging and integral field spectroscopy, and the latter primarily by reflected light with ZIMPOL.

Design goals include access to angular scales 0.1–3 arcsec from the host star, and the detection of giant planets at contrasts of  $10^{-6}$  at  $J = 6$  mag and  $\Delta\theta \sim 0.5$  arcsec. It aims to detect young (10 Myr)  $5M_J$  planets at 40 pc. For mature planets, the most promising targets lie within 5–10 pc, with  $a \gtrsim 3 - 5$  au.

**Instrument** SPHERE developed from ESO’s call for an exoplanet imager in 2001, illustrating the decade-long development time typical of these complex instruments. A synthesis of two earlier concepts, CHEOPS and Planet Finder, SPHERE is an extreme adaptive optics system and coronagraphic facility feeding three instruments: IRDIS, IFS, and ZIMPOL.

The common path system receives light from the telescope, and provides stabilised, AO-corrected, and coronagraphic beams to the three sub-instruments. The adaptive optics system comprises a  $41 \times 41$  actuator deformable mirror, and a  $40 \times 40$  lenslet Shack-Hartmann wavefront sensor covering 450–950 nm (Fusco et al., 2006b,c; Petit et al., 2008; Martínez et al., 2010; Sauvage et al., 2016). The modular coronagraphic package includes an (achromatic) four-quadrant phase mask (Boccaletti et al., 2008b; Galicher et al., 2011a), a classical Lyot coronagraph, and an apodised Lyot coronagraph (Boccaletti et al., 2008a; Carbillet et al., 2011; Guerri et al., 2011).

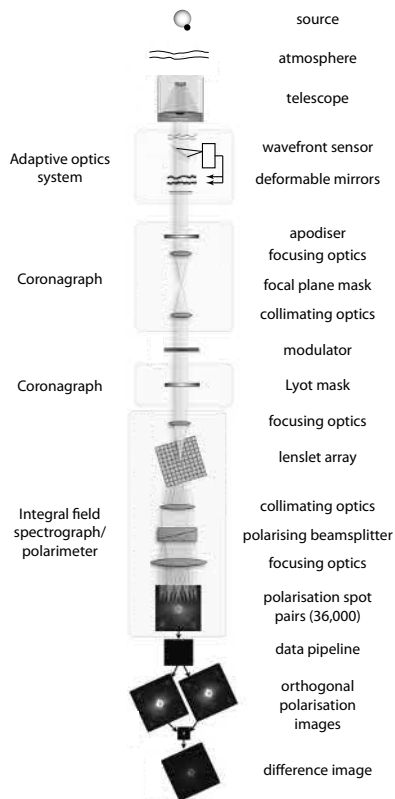


Figure 7.11: Schematic of the Gemini-GPI integral field polarimeter. The light is optically divided by the lenslet array prior to dispersion, largely eliminating sensitivity to non-common-path errors and chromatic birefringence, and thus producing a difference image with highly-suppressed speckles. From Perrin et al. (2015, Figure 1), by permission of IOP Publishing/AAS.

The integral field spectrograph (IFS, Claudi et al., 2008; Mesa et al., 2011; De Caprio et al., 2012; Zurlo et al., 2014; Mesa et al., 2015) provides a data cube of 30 monochromatic images either at spectral resolution  $R \sim 50$  between  $0.95\text{--}1.35\ \mu\text{m}$  (Y-J) or  $R \sim 30$  between  $0.95\text{--}1.65\ \mu\text{m}$  (Y-H).

The infrared dual-band imager and spectrograph (IRDIS, Dohlen et al., 2008; Zurlo et al., 2014) provides classical imaging, dual-band imaging (Vigan et al., 2010, 2012a), dual-polarisation imaging (Langlois et al., 2014), and long-slit spectroscopy (Vigan et al., 2008, 2012a, 2016b), either between  $0.95\text{--}2.32\ \mu\text{m}$  with  $R \sim 50$  (LRS), or between  $0.95\text{--}1.65\ \mu\text{m}$  with  $R \sim 350$  (MRS). The specific challenges of coupling long-slit spectroscopy with coronagraphy, and a resulting apodised long-slit coronagraph, are described by Vigan et al. (2013).

The Zurich imaging polarimeter (ZIMPOL, Thalmann et al., 2008b; Joos et al., 2011; Roelfsema et al., 2011) provides diffraction-limited imaging and differential polarimetric imaging at  $< 30$  mas resolution in the visible.

**Gemini Planet Imager** GPI, on Gemini-South, shares a number of key features with SPHERE (Macintosh et al., 2008; McBride et al., 2011). It is a more compact design, including extreme adaptive optics with MEMS deformable mirrors, 1800 actuators,  $0.18\ \text{m}$  sub-apertures,

and a control rate of  $2\ \text{kHz}$  (Poyneer et al., 2011). It uses an apodised pupil Lyot coronagraph to target a planet contrast of  $10^{-7}$  at  $I = 6$  mag, and an inner working angle of  $0.13\ \text{arcsec}$  (Soummer et al., 2006, 2011b; Thomas et al., 2011), over a wavelength range  $1\text{--}2.4\ \mu\text{m}$ . In contrast to SPHERE's installation at the VLT's Nasmyth platform, GPI is mounted at the (moving) Cassegrain focus, and includes a dedicated calibration system which integrates the measurement of low- and higher-order aberrations on the time scales of minutes.

Lenslet-based integral field spectroscopy at  $R = 45$  can be used for exoplanet confirmation and characterisation (Chilcote, 2014). Polarimetric imaging is also provided (Perrin et al., 2015, see Figure 7.11).

First-light was in 2013 November (Macintosh et al., 2014). An overview of results is given in Section 7.9.

**Prospects** For plausible assumptions about gas giant distributions at large  $a$ , McBride et al. (2011) estimated that GPI should detect more than 10% of gas giants with  $M_p > 0.5M_J$  around stars younger than 100 Myr with  $d < 75\ \text{pc}$ , and  $> 50\%$  of systems younger than 1 Gyr with  $M_p > 8M_J$  and  $a > 15\ \text{au}$ . A few tens should be sufficient to discriminate how planets form.

Planet detectability in the  $\beta$  Pic moving group, a promising target in view of its youth (12 Myr) and proximity (35 pc), has been assessed based on brightness models assuming formation by core accretion or by disk instability. Results suggest that companions of many FG-type stars should be detectable, while the four A stars are too bright (Kataria & Simon, 2010).

**Subaru-HiCIAO** Subaru is also equipped with a High Contrast Coronagraphic Imager for Adaptive Optics (HiCIAO), although its original AO188 adaptive optics system, with 188 actuators, does not reach the high Strehl ratios of SPHERE and GPI. It uses a Lyot coronagraph with mask diameter  $4.8\lambda/D$  as baseline, a polarisation channel, and a  $2024 \times 2024$  HgCdTe array with a pixel scale of  $0.01\ \text{arcsec}$  operating in the JHK bands, giving contrasts of  $4 \times 10^{-6}$ , and an inner working angle of  $0.1\ \text{arcsec}$  (Tamura et al., 2006; Tamura, 2009). Upgrade to a 1024 actuator system, AO1024, has been indicated.

Post-processing uses angular differential imaging, simultaneous differential imaging using  $\text{CH}_4$  and  $[\text{Fe II}]$  bands, and polarisation differential imaging. First light was in December 2008. The HiCIAO survey, using 120 nights of Subaru time over 5 years, started in October 2009. An overview of results is given in Section 7.9.

**CHARIS** The Coronagraphic High Angular Resolution Imaging Spectrograph is a high-contrast near-infrared integral field spectrograph under construction for Subaru, operating over  $0.9\text{--}2.4\ \mu\text{m}$  (Peters et al., 2012; McElwain et al., 2012; Peters-Limbach et al., 2013; Groff et al., 2014, 2015). It is implemented behind a new (mid-2013) coronagraph and MEMS-based extreme adaptive optics system, SCEXAO (Martinache et al., 2012b; Jovanovic et al., 2015), itself located behind the existing adaptive optics module AO188. SCEXAO uses a pyramid wavefront sensor, active speckle nulling, and a choice of coronagraphs (PIAA, vector vortex, 8OPM, 4QPM; see Table 7.1).

CHARIS includes a low-spectral-resolution mode covering the full wavelength range, and a high-resolution mode within

a single band, providing high sensitivity, as well as detailed prospects for atmospheric characterisation. Similar in concept to SPHERE and GPI, and described as Subaru's 'third-generation' exoplanet imaging instrument (following HiCIAO), it will be the only such facility on an 8-m class telescope in the northern hemisphere.

### 7.6.3 Extremely large telescopes

Exoplanet imaging and spectroscopy have been important science goals for all of the proposed extremely large optical aperture telescopes.

The advent of the 'extremely large telescope' era included ambitious concepts for a 100-m *Overwhelmingly Large Telescope* (OWL), providing  $\lambda/D \sim 1$  mas in the V-band, and yielding  $S/N = 10$  at 35 mag in 1 h for imaging, and at 30 mag in 3 h for  $R = 1000$  spectroscopy (Gilmozzi et al., 1998, 2002; Hawarden et al., 2003; Fusco et al., 2006d; Hainaut et al., 2007). Various exoplanet imaging studies were carried out (Vérinaud et al., 2006; Lenzen et al., 2006; Berton et al., 2006b; Fusco et al., 2006d).

While apertures of 100 m are no longer under active consideration, there are three telescopes with apertures significantly exceeding the current 10-m class under development: the European Extremely Large Telescope (E-ELT), the Thirty Meter Telescope (TMT), and the Giant Magellan Telescope (GMT). They are described briefly, along with some broad considerations of their expected planet detection capabilities, below.

**Image structure** Exoplanet detection challenges of the extremely large telescopes are technically similar to those for the 10-m class. Results will depend sensitively on reaching very high Strehl ratios, and on the success of diffraction and speckle suppression techniques to deliver the highest contrasts (Cavarrac et al., 2006; Hainaut et al., 2007).

For a Strehl ratio  $S$ , simulations show a central image spike resembling a diffraction-limited image containing some  $S\%$  of the total light, less a modest fraction diverted into wider components of the telescope point-spread function. The spike is surrounded by a halo containing the residual light distributed like an unmodified seeing disk, i.e. with a generally Lorentzian distribution. This halo overlies, and within the seeing disk generally dominates, the fainter wings of the telescope point-spread function.

The wings combine the light diffused by the small-scale imperfections of the optics and any accumulated dust, as well as the light diffracted by the central obstruction and geometric edges of the mirrors and supporting structures. The diffracted light strongly dominated the uncorrected seeing light.

For adaptive optics-corrected images, the detailed structure of the halos is more complex. At large radii they are composed of the rapidly varying 'classical' speckles, with size  $\sim \lambda/D$ . Less well-understood 'super-speckles' occur closer to the first 2–3 diffraction rings; they are larger, brighter, less rapidly variable and therefore less likely to average out on a long-exposure image. At the wavelengths of interest they should not, however, occur more than 10 mas from the image centre, corresponding to 0.1 au at a distance of 10 pc. While techniques such as simultaneous differential imaging may cancel these super-speckles, their noise contribution remains even after subtraction, and is typically the strongest noise source in the 5–15  $\lambda/D$

Table 7.2:  $V$  magnitude and separation  $\alpha$  (arcsec) relevant for ELT observations. Modeled planet/star contrasts are in the range  $\sim 10^{-8}$  to  $10^{-9}$ . From Perryman et al. (2005, Table 6).

Distance (pc)	Star (mag)		Hot Jupiter 0.2 au	Earth 1 au	Jupiter 5 au
10	4.8	$V$	24.1	27.9	25.8
		$\alpha$	0.020	0.100	0.500
25	6.8	$V$	26.1	29.9	27.8
		$\alpha$	0.008	0.040	0.200
50	8.3	$V$	27.6	31.4	29.3
		$\alpha$	0.004	0.020	0.100
100	9.8	$V$	29.1	32.9	30.8
		$\alpha$	0.002	0.010	0.050

region. This can only be reduced by improving the Strehl ratio of the adaptive optics system.

**Exoplanet detection** Detection of a terrestrial-like planet is made possible, in principle, by its relatively large angular separation from the star's central diffraction peak. At separations of 100 mas (1 au at 10 pc) only the sky background, the wider scattering components of the intrinsic point-spread function, and the adaptive optics halo contribute to the background.

The orbital radius at which an exoplanet is detectable is then bounded by two effects. At the inner extreme, the bright inner structures of the stellar image reduce sensitivity below 10–20 mas (1 au at 50–100 pc), so that within these angles only young self-luminous exoplanets could be detected. At the outer extremes, reflected starlight falls off with increasing orbital distance. Some relevant angular scales are shown in Table 7.2.

Assuming that a planet is detected only beyond an angular distance of  $5\lambda/D$  from the host star, the volume of space accessible is proportional to  $D^3$ . The numbers for G stars range from about about 900 for 100 m apertures to 25 for 30 m. For background-limited measurements, and a planet lying within the uncorrected stellar light, the time to achieve a given  $S/N$  scales as  $(S/N)^{-2}$ , i.e.  $S \propto D^2$ , background  $\propto D^2$ , and diffraction-limited pixel size  $\propto D^{-2}$ , so that  $S/N \propto D^2$  and  $t \propto D^{-4}$ . Thus a 30 m aperture would require 120 times longer than a 100 m to observe a planet accessible to both.

With specific assumptions about the instrumental aberrations, Chelli (2005) derived expressions for the signal-to-noise ratio on the planet flux, for direct and differential imaging, in the presence of speckle noise and photon noise due to the residual stellar halo. For an Earth at 10 pc to be detected with  $S/N = 5$  in 12 h, a 100-m telescope would require the intensity of the incoherent halo at 0.1 arcsec radius to be reduced from that of the central source by a factor  $1.2 \times 10^6$ . For a 30-m telescope, the corresponding factor is  $1.3 \times 10^7$ .

**Distance limits** The limiting distances at which particular observations can be performed depend on these various assumptions. Estimates of the numbers of single G and early K stars that would be suitable for imaging and spectroscopy of Earth- and Jupiter-like planets were made in the context of an ESA-ESO Working Group in 2005, and are given in Table 7.3.

According to the study made at that time, 30–40-m ELTs will not be capable of imaging Earth-like planets, and will be challenged to provide useful spectroscopy even for very nearby Jupiter-type planets. More massive and more widely separated exoplanets will be measurable, and form the focus of specific instrumentation efforts now underway.

**European Extremely Large Telescope (E-ELT)** The *European Extremely Large Telescope* comprises a reflecting telescope with a 39.3-m diameter segmented primary mirror (it was down-sized from 42-m in 2011) and a 4.2-m diameter secondary mirror. It will be supported by adaptive optics, six laser guide star units and multiple large science instruments. In 2010, first light was targeted in 2018; the current target date is 2024.

**Instrumentation** The proposed multi-conjugate adaptive optics module for the E-ELT, MAORY (Diolaiti et al., 2010; Arcidiacono et al., 2014; Diolaiti et al., 2016), is foreseen to provide average Strehl ratios of  $\sim 0.5$  over a corrected field of view up to 2 arcmin at 0.8–2.4  $\mu\text{m}$ . It will operate with six Na laser guide stars, and three levels of wavefront correction comprising the telescope adaptive mirror, and two post-focal deformable mirrors conjugated at heights of 4 and 12.7 km.

Two exoplanet imaging instruments are under study. EPICS (Exoplanet Imaging Camera and Spectrograph) targets near-infrared, high-contrast ( $10^8 - 10^9$ ), and high resolution ( $\sim 10$  mas) to 30 mas from the host star (Vérinaud et al., 2006; Kasper et al., 2008).

METIS (Mid-Infrared ELT Imager and Spectrograph) targets the mid-infrared, 3–20  $\mu\text{m}$  (Brandl et al., 2008, 2014). Coronagraph studies are ongoing (Carlomagno et al., 2016). METIS could image  $\sim 20$  already-known radial velocity planets, with others expected from ongoing radial velocity surveys and from Gaia (Quanz et al., 2015b). Extrapolating statistics for close-in planets found by Kepler, METIS might detect  $\sim 10$  small planets with  $T_{\text{eff}} \sim 200 - 500$  K around nearby stars.

**Thirty Meter Telescope (TMT)** The *Thirty Meter Telescope*, originally planned for a site in Mauna Kea (Hawaii) with first light on a comparable time scale as for E-ELT (Crampton et al., 2009), is currently listed as ‘postponed’ due to site permit issues. The Roque de los Muchachos Observatory, La Palma, is considered as an alternative location.

**Instrumentation** The adaptive optics module foresees a 2–4 kHz pyramid wavefront sensor, driving a  $10^4$  ( $128 \times 128$ ,  $d = 0.24$  m) actuator deformable mirror, and targeting Strehl ratios of 0.9 (Vasishet et al., 2006).

The Planet Formation Imager (PFI, Macintosh et al., 2006; Macintosh, 2007) for TMT has similar contrast and angular scale objectives as E-ELT-EPICS. It includes a dedicated integral field spectrograph, with  $R \sim 70$  and a  $2 \times 2$  arcsec<sup>2</sup> field. The role of a coronagraphic mask (and diffraction suppression) is implemented as a (dual-stage shearing) nulling interferometer, providing a small inner working angle  $\sim 3\lambda/D$ . Further contrast enhancement, by suppression of the quasi-static speckle pattern resulting from other wavefront errors, employing a post-coronagraphic wavefront sensor driving a dedicated deformable mirror, is under study.

Amongst proposed instruments was the Second-Earth Imager (SEIT), also incorporating extreme adaptive optics, a coronagraph, and post-processing techniques to achieve high contrast at small inner working angles, and focusing on simultaneous spectroscopy of the star and planet (Matsuo et al., 2012). A prototype for the Kyoto 4-m telescope, SEICA (Second-generation Exoplanet Imager with Coronagraphic Adaptive optics), has also been considered (Matsuo et al., 2014).

Table 7.3: Indicative distance limits and numbers of stars as a function of exoplanet mass and primary mirror diameter, and based on simplistic assumptions, for both imaging (Im) and spectroscopy (Sp). From Perryman et al. (2005, Table 7).

D (m)		Earth-type		Jupiter-type	
		Im	Sp	Im	Sp
30	$d$ (pc)	10	–	70	5
	$n$ (★)	22	0	6 800	3
60	$d$ (pc)	22	–	120	18
	$n$ (★)	210	0	35 000	170
100	$d$ (pc)	40	15	500	35
	$n$ (★)	1200	67	2 500 000	860

**Giant Magellan Telescope (GMT)** The *Giant Magellan Telescope* will consist of seven 8.4-m primary segments, with the resolving power of a 24.5-m primary mirror and collecting area equivalent to a 22.0-m telescope. As of the end of 2017, five mirrors have been cast, construction of the summit facility at Las Campanas has begun, with first light/completion in the period 2021–25 (Johns, 2008). Various exoplanet programmes have been described (Codona, 2004; Angel et al., 2006; Close, 2007).

**Indicative prospects** All of these planned extremely large telescopes aim to exploit AO-assisted, diffraction-limited observations, with high-contrast near-infrared instruments under study. Initial assessments suggest that with reasonable technological advances, they will be sensitive to separations and contrast levels unprecedented for optical/infrared telescopes.

The proposed high-contrast instruments evidently vary in design and performance details. Crossfield (2013) simulated a more generic ‘giant segmented mirror telescope’ using the analytic relations of Guyon (2005). These assume that the instrument corrects both phase and amplitude errors (sensed via a Mach-Zehnder pupil plane wavefront sensor), that the wavefront sensing and science wavelengths are identical to minimise chromatic contrast errors, and that observational and post-processing techniques suppress the instantaneous PSF contrast by a factor of 30 at all separations. A further ingredient for the simulations is the occurrence rate of short-period planets around main sequence stars. The Kepler results now constrain this as a function of  $P$ ,  $R_p$ , and stellar  $T_{\text{eff}}$ .

With these assumptions, Crossfield (2013) predicts that  $\sim 10$  planets with  $R_p = 1 - 8R_{\oplus}$  and  $T_{\text{eq}} \leq 400$  K should be accessible within 8 pc, with roughly similar numbers for both near-infrared observations of scattered light and mid-infrared observations of planetary thermal emission. Assuming that planets with  $R_p = 1 - 2R_{\oplus}$  and  $2 - 4R_{\oplus}$  occur with equal frequency, there is a 40% probability that an Earth or Venus analogue, with  $R_p = 1 - 2R_{\oplus}$  and  $T_{\text{eq}} = 200 - 250$  K, will be accessible.

Thermal infrared observations will characterise the thermal emission spectra of the short-period planets

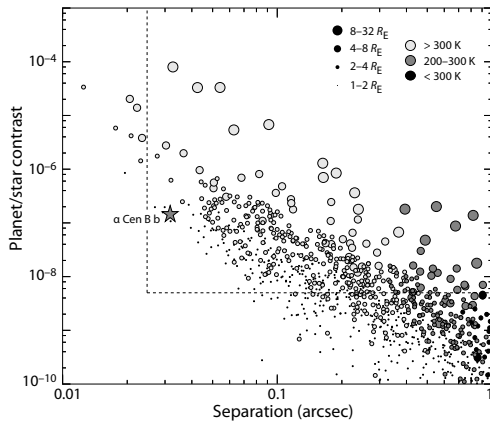


Figure 7.12: Simulated planet populations for  $\alpha$  Cen B, assuming a generic ‘giant segmented mirror telescope’ observing at  $1.2\ \mu\text{m}$  with an instrument similar to TMT-PFI or TMT-SEIT, and a probability distribution of planets informed by the Kepler results. Planets above and to the right of the dashed line would be accessible to high-contrast spectroscopy. The star symbol indicates  $\alpha$  Cen B b itself, assuming  $R_p = 1.1R_\oplus$ . Circle size and shading refer to a simulated planet’s  $R_p$  and  $T_{\text{eq}}$  as shown in the legend. Most of the simulated planets are detected in scattered starlight, although thermal emission contributes to the shortest-period planets, including  $\alpha$  Cen B b. From Crossfield (2013, Figure 1), reproduced with permission © ESO.

(and thus, via radiometric radii, break the radius–albedo degeneracy inherent in reflected light observations), as well as significantly improving the prospects of finding Earth or Venus analogues.

Several planets discovered from radial velocity surveys will be accessible, including the low-mass  $\alpha$  Cen B b (Figure 7.12) and, depending on albedos, (some of the) planets orbiting GJ 139, GJ 876, and  $\tau$  Cet.

#### 7.6.4 Imaging from the Antarctic

The Antarctic Plateau provides excellent conditions in terms of telescope acuity and sensitivity across optical to sub-mm wavelengths. High atmospheric transparency and low sky emission result from the cold dry air. It yields one long observing ‘night’ per year, with complete darkness and 80% clear skies in June–July, decreasing to 7 h darkness during March and October, although with an extended ‘twilight’ period.

Science currently conducted from the Antarctic includes optical, infrared, terahertz and sub-mm astronomy, solar astronomy, and measurements of cosmic microwave background anisotropies, and of high-energy cosmic rays, gamma rays, and neutrinos (e.g. Burton, 2010; Burton et al., 2015b). Exoplanet transit detection prospects are considered in Section 6.4.4.

**Plateau stations** Astronomical activities operate at four plateau stations: Amundsen–Scott at the South Pole (USA), Concordia at Dome C (FRA/ITA), Kunlun at Dome A (CHN), and Fuji at Dome F (JPN). Dome C (elevation 3250 m, latitude  $-75^\circ$ )

opened for winter operations in 2005 after a decade-long construction phase (Figure 7.13), and is the polar site best characterised astronomically (e.g. Aristidi et al., 2003; Storey et al., 2003; Lawrence et al., 2004). Ambient temperatures range from 195–235 K, resulting in low and stable thermal emission. Low surface winds, with a median of  $2.7\ \text{m s}^{-1}$  and below  $5\ \text{m s}^{-1}$  for >90% of the time, result in low free-air turbulence, with a quasi-absence of jet streams inside the polar vortex. Future plans for Dome C have been formulated within the EU-funded ARENA consortium (2006–09), which concluded its activities with a development roadmap (Epchtein, 2010).

Even better conditions may exist at Domes A and F (Lawrence, 2004b; Hu et al., 2014), with gains up to  $10^3$  in various performance indicators compared to the best mid-latitude sites, such as Mauna Kea and Chajnantor. Dome A is the highest location on the plateau, at 4083 m. First visited only in 2005, China began construction of the Kunlun station in 2009. Observations are ongoing using an Australian robotic observatory (Wang et al., 2013b; Yuan et al., 2014; Zong et al., 2015), and there are plans for other facilities (Gong et al., 2010).

**Performance gains** Broadly, Antarctica offers the following performance gains compared to excellent temperate latitude sites (Storey, 2009; Burton, 2010): (i) atmospheric seeing a factor 2–3 $\times$  better (above a 10–40 m boundary layer), providing better spatial resolution and point-source sensitivity; (ii) an isoplanatic angle some 2–3 $\times$  larger, from the 2.9 arcsec normalised value for Paranal, to some 5.9 arcsec, providing better adaptive optics sky coverage using natural guide stars; (iii) improved atmospheric coherence time, some 2.5 $\times$  longer, resulting in increased sensitivity for adaptive optics and interferometry; (iv) reduced scintillation noise, by a factor 3–4, resulting in more precise photometry; (v) reduced infrared sky background, by a factor 20–100, resulting in increased infrared sensitivity and improved photometric stability; (vi) extremely dry air, a factor 3–5 $\times$  lower with  $250\ \mu\text{m}$  precipitable  $\text{H}_2\text{O}$  vapour typical, resulting in improved infrared and sub-mm transmission windows; and (vii) dust aerosols some factor of 50 lower, resulting in better infrared windows and improved sky stability.

The combination of a cold and dry atmosphere results in infrared photometric gains of up to 25 in the K and L bands, i.e. an Antarctic 1.8-m telescope is more efficient than an 8-m telescope at a temperate site. In the H and N bands the gains (of order 3) are significant although less dramatic.

**Exoplanet imaging** Of specific interest for exoplanet imaging is the confinement of most of the atmospheric turbulence to a thin layer just above the ice. This creates conditions that are particularly favourable for adaptive optics wavefront correction, as well as providing telescopes with excellent seeing if raised above the boundary layer. Specific studies have been made of the performance of such ground-layer adaptive optics systems (e.g. Lawrence, 2004a; Travouillon et al., 2009; Carbillot et al., 2010; Masciadri et al., 2010a; Aristidi et al., 2015).

There are no confirmed plans for dedicated exoplanet imaging experiments from the Antarctic. Various studies have been made, in particular based on nulling interferometry (Swain et al., 2003; Lawrence et al., 2006; Valat et al., 2006; Lloyd, 2006). An ambitious proposal for an interferometer at Dome C, KEOPS, calling for an array of 39 1–2 m telescopes spread over km baselines and operated in the thermal infrared, was aimed at characterising all exo-Earths within 1 kpc (Vakili et al., 2005). A concept for a high-angular resolution wide-field Polar Large Telescope (PLT) in the near thermal infrared ( $2.3\text{--}5\ \mu\text{m}$ ) has also been considered (Epchtein et al., 2011; Abe et al., 2013b).

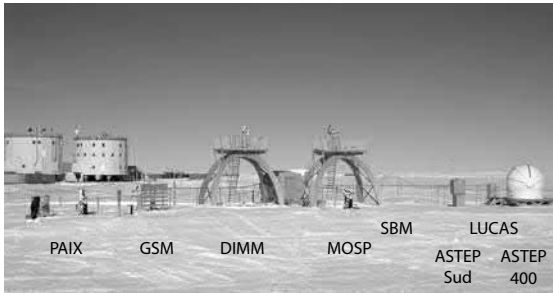


Figure 7.13: The French–Italian Concordia Station at Dome C, and the experiments of the Concordiaastro site characterisation programme in 2008: PAIX (extinction), GSM and DIMM (seeing), MOSP (turbulence outer scale), SBM (sky brightness), ASTEP Sud (photometry), ASTEP 400 and LUCAS (spectra of Earth-shine off the Moon). The twin towers of the station are seen at the rear. Courtesy Karim Agabi.

### 7.6.5 Interferometry

Diffraction-limited resolution over baselines of tens or hundreds of meters can be achieved using amplitude interferometry that combines light, in phase (to some 1–10 mrad), from separate telescopes (e.g. Quirrenbach, 2001; Monnier, 2003; Millour, 2008; Quirrenbach, 2009; Le Bouquin & Absil, 2012; Wolf et al., 2012). By virtue of their long optical baselines and high angular resolution, all major interferometers have embraced exoplanet imaging as part of their scientific goals (§7.9).

For example, various observations of exoplanet host stars with CHARA have been used to constrain stellar parameters, companion masses, and assess prospects for the direct detection of hot Jupiters (e.g. Baines et al., 2010, 2011; Zhao et al., 2011; Ligi et al., 2012). Searches for exozodiacal light/dust have been reported in a series of papers (Nuñez et al., 2017, and references).

**VLT-I, Keck-I, LBT-I** Three large-aperture systems have been designed to operate with interferometric combination of the individual telescope beams:

**ESO–VLTI:** the ESO Very Large Telescope Interferometer (VLTI) at Cerro Paranal, Chile. This has four 8-m and four auxiliary 1.8-m telescopes over a 200-m baseline (Glindemann et al., 2003). AMBER is a first-generation interferometric instrument for which exoplanet detection has been considered in phase-closure mode and through the use of colour-differential photometry (Joergens & Quirrenbach, 2004; Millour et al., 2006; Vannier et al., 2006; Matter et al., 2010). The proposed second-generation instrument VLTI Spectro-Imager (VSI, Renard et al., 2008), which targeted exoplanet imaging using low spectral resolution at angular scales down to 1.1 mas in the near-infrared, was not approved. The adopted narrow-angle 10  $\mu$ s astrometric mode, PRIMA, and its associated exoplanet programme, ESPRIT (Launhardt et al., 2008), was cancelled by ESO in 2014. PIONIER (Precision Integrated-Optics Near-infrared Imag-

**Long-baseline small-aperture interferometers:** Operational or developmental facilities in the optical or near-infrared are: the 30-m baseline 2-element Mitaka Optical and Infrared Array (MIRA, Yoshizawa et al., 2006; Ohishi et al., 2008); the 75-m baseline 3-element 1.65-m telescope Infrared Spatial Interferometer (ISI, Townes & Wishnow, 2008); the 160-m baseline Sydney University Stellar Interferometer (SUSI, Davis et al., 2006); the 330-m 6-element 1-m telescope Y-configuration CHARA interferometer of Georgia State University at Mount Wilson (ten Brummelaar et al., 2003); the 340-m baseline 10-element 1.4-m telescope Y-configuration Magdalena Ridge Observatory Interferometer, under development (MROI, Buscher et al., 2006a; Creech-Eakman et al., 2008, 2012); and the 437-m baseline 6-element US Navy Prototype Optical Interferometer (NPOI, Johnston et al., 2006a).

Interferometers no longer operational include the 32-m Mark III interferometer at Mount Wilson, operational 1987–1992 (Shao et al., 1988); the 38-m Infrared-Optical Telescope Array at Mount Hopkins, operational 1993–2006 (IOTA, Schloerb et al., 2006); the 65-m GI2T of the Observatoire de la Côte d’Azur, closed in 2006 (Mourard et al., 2006); the 60-m Cambridge Optical Aperture Synthesis Telescope, operational 1993–2005 (COAST, Buscher et al., 2006b); and the 110-m baseline Palomar Testbed Interferometer, operational 1995–2009 (PTI, Akeson, 2006).

ing ExpeRiment, Le Bouquin et al. 2011) combines the light from 4 telescopes in the near-infrared, and has been used for searches for planets and debris disks around various stars including Fomalhaut,  $\tau$  Cet, and  $\beta$  Pic (Absil et al., 2011b; Defrère et al., 2012; Marion et al., 2014; Ertel et al., 2014, 2016).

**Keck–I:** the Keck Observatory Interferometer in Hawaii, operated two 10-m and four auxiliary 2-m telescopes over an 85-m baseline (Wizinowich et al., 2006a; Colavita et al., 2013). As of mid-2012, it is no longer operational.

**LBT–I:** the Large Binocular Telescope, Mt Graham, Arizona, has two 8.4-m telescopes on a common mount with a 14.4-m baseline (Hill, 2010). Binocular imaging began in early 2008, first light for adaptive optics imaging for the two (separate) telescopes in 2010, and interferometric cophasing (in nulling mode at 8–13  $\mu$ m) in 2015 (Defrère et al., 2015, 2016). It is being used for the HOSTS survey (Hunt for Observable Signatures of Terrestrial Systems) for zodiacal dust in the habitable zones of nearby solar-type stars (Danchi et al., 2016).

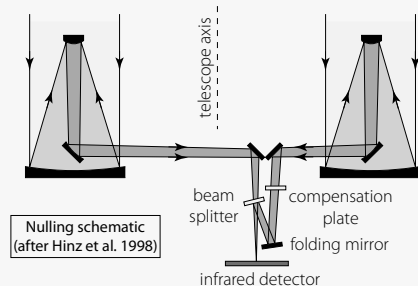
**Nulling interferometers** A nulling mode (see box) has been implemented at some of the major optical interferometers. Direct detection prospects for known exoplanets in such a mode has been evaluated for Keck–I, VLTI–I, and LBT–I (Langlois et al., 2006). Nulling operations were first reported at the MMT using two sub-apertures (BLINC, Hinz et al., 2000).

For Keck–I, the Keck Interferometric Nuller (KIN, 8–13  $\mu$ m) made commissioning observations between 2004–07, with science observations between 2008–11 covering a 40-star exozodiacal survey as well as young



**Nulling interferometry:** *Nulling* is one mode of interferometric operation considered for exoplanet imaging, first proposed by Bracewell (1978) and Bracewell & MacPhie (1979). It introduces destructive interference between the pupils of two telescopes, or the sub-apertures of a single telescope, for an on-axis star.

Identical path lengths through the two beams leads to an interference maximum for an on-axis source. Off-axis rays traverse different optical path lengths, resulting in circular interference fringes with a bright central maximum. Introducing a phase difference of  $\pi$  rad in one of the paths suppresses the central maximum. The transmission pattern on the sky, for monochromatic light, is a sequence of fringes given by  $T(\theta) = \sin^2(\pi\theta D/\lambda)$ . By varying the baseline  $D$ , a range of constructive interference angles can be examined for the presence of an off-axis source.



On the ground, nulling requires adaptive optics and operation at mid-infrared wavelengths, around  $5\text{--}10\ \mu\text{m}$ , because rapid atmospheric path length differences of order a few  $\mu\text{m}$  otherwise shift the interference randomly between constructive and destructive states.

Various configurations have been described (e.g. Hinz et al., 1998; Wallace et al., 2000; Hinz et al., 2001; Martin & Booth, 2010b; Hénauld, 2011; Hicks, 2016). Constraints on errors in the required  $\pi$  rad phase difference can be relaxed if more than two beams are recombined (Mieremet & Braat, 2003; Lane et al., 2006). Closure phase measurements for a nulling interferometer with three or more telescopes may also be possible (Danchi et al., 2006).

stellar objects and hot debris disks (Mennesson et al., 2006; Barry et al., 2008b; Colavita et al., 2009; Millan-Gabet et al., 2011; Mennesson et al., 2012). Keck nuller operations were terminated in 2011.

Nulling interferometry has been operational at the Large Binocular Telescope since 2015 (LBT-I, Hinz et al., 2008, 2014; Defrère et al., 2016). Nulling operation is also foreseen for GMT (Angel et al., 2006).

A nulling prototype for Darwin, GENIE, was considered but not implemented for VLTI (Gondoin et al., 2008; Pelat et al., 2010; Absil et al., 2011a). A similar prototype was considered for TPF-I (Martin & Booth, 2010a).

**Long-baseline small-aperture interferometers** The discovery space for small-aperture interferometers is limited by the faint exoplanet flux. A list of operational systems is given in the accompanying box, page 348.

**Extension to km-baselines** Several concepts have been proposed to extend such facilities to scales of a km or more (see,

e.g., §7.8.2), but their realisation is challenging either on the ground or in space. Problems include its restricted sensitivity, the demands of optical and atmospheric stability to a fraction of a wavelength, the need to cover many interferometric baselines (given that optical light cannot be copied with retained phase, but has to be split up, and diluted, by beamsplitters to achieve interference among multiple telescope pairs), and technical challenges such as the need for long delay lines to compensate the changing path difference between telescopes.

**Stratospheric observations** Bridging the technological and environmental conditions between ground and space, stratospheric observations have been proposed. A coronagraphic camera with active optics at an altitude of 35 km, Artemis/UHST, was considered by Ford et al. (2002). Traub et al. (2008) showed that free-atmospheric and locally-generated turbulence should not limit observations at  $10^{-9}$  contrast for star-planet separations of 0.5 arcsec.

**Intensity interferometry** Some considerations of intensity interferometry are given in Section 7.8.1.

**Quantum interferometry** The detection and processing of (quantum-mechanically) entangled-photon pairs has been proposed as a way of measuring the correlation of quantum states, in the near infrared, between two spatially-separated telescopes, and at very high photon sensitivities, yielding angular resolution at the  $\mu\text{as}$  level (Riaud, 2012b).

## 7.7 Space-based imaging instruments

The contribution of HST, Spitzer, and (the future) JWST to transit photometry and spectroscopy, and a short description of each mission, is given in §6.10 and §6.8.3. This section refers only to imaging-related considerations, and specifically to their coronagraphic capabilities.

### 7.7.1 Existing space telescopes

**HST** For exoplanet research, the Hubble Space Telescope (§6.10.2) has been particularly relevant in the study of exoplanet transits and eclipses (Chapter 6). For imaging studies, NICMOS (near-infrared Camera and Multi-Object Spectrometer), operational from 1997–99 and 2002–08, provided an occulting spot of 0.6 arcsec diameter. It was used to confirm the discovery of 2M J1207 b (Song et al., 2006, §7.10).

ACS (Advanced Camera for Surveys) High Resolution Channel, operational from 2002–06, included a coronagraphic mask with two occulting spots of diameter 1.8 and 3 arcsec (Ford et al., 1998). This mode was used for the detection of Fomalhaut b (Kalas et al., 2008, §7.10).

STIS (Space Telescope Imaging Spectrograph) operational from 1997–2004, included focal plane wedges and a Lyot stop providing white-light coronagraphy between  $0.2\text{--}1.0\ \mu\text{m}$  (Grady et al., 2003).

**Spitzer** The imaging capabilities of Spitzer (launched 2003, see further details in Section 6.10.5) is determined by the diffraction limit of the relatively small 0.85-m telescope (1.5 arcsec at  $6.5\ \mu\text{m}$ ). It has therefore had limited application for direct exoplanet imaging, although

it has been widely used for the detection and imaging of circumstellar and debris disks, as well as its important capabilities for transiting systems (Chapter 6). Its sensitivity corresponds to the detection of dust around a solar-type star at 30 pc at levels below that inferred to exist in small grains in the Kuiper belt ( $6 \times 10^{19}$  kg).

High-contrast imaging efforts, all unsuccessful, have included searches for planets around Vega, Fomalhaut, and  $\epsilon$  Eri, with a typical sensitivity of  $2M_J$  at 150 au (Janson et al., 2015), and archival searches around 73 young nearby stars with typical sensitivities to 0.5–13 $M_J$  planets at 100–1000 au (Durkan et al., 2016).

**PICTURE** The PICTURE missions aim to characterise scattered light from debris disks using several high-contrast imaging techniques (Mendillo et al., 2012): sounding rocket (the Planet Imaging Concept Testbed Using a Rocket Experiment) and balloon flights of a visible nulling coronagraph, as well as a balloon flight of a vector vortex coronagraph (the Planetary Imaging Concept Testbed Using a Recoverable Experiment–Coronagraph, PICTURE–C). The PICTURE–B sounding rocket was designed to directly image the exozodiacal light and debris disk around  $\epsilon$  Eri, using a 0.5-m SiC primary mirror, deformable secondary, and a visible nulling coronagraph combined with a fine pointing system capable of 5 mas stability. Launched from White Sands, New Mexico on 2015 November 24, the experiment did not achieve nulling (Chakrabarti et al., 2016).

### 7.7.2 Future space telescopes

**JWST** The James Webb Space Telescope (JWST, see Section 6.8.3) has a 6.5-m diameter (gold-coated beryllium) primary mirror, and a collecting area five times as large as HST. Two of the four instruments (NIRCam and MIRI) have coronagraphs, with high-contrast imaging amongst their primary goals (Beichman et al., 2010). JWST is scheduled for launch in mid-2020.

**Instrumentation** NIRCam, the near-infrared camera, provides coronagraphic imaging from 1–5  $\mu\text{m}$  using a Lyot coronagraph with five apodised occulting masks at the telescope focus (three circular and two wedge-shaped), and matching aperture masks (Lyot stops) at subsequent images of the telescope pupil (Krist et al., 2009). At around 4.6  $\mu\text{m}$ , and after angular (roll) differential imaging, contrast levels of  $10^{-5}$ – $10^{-6}$  at separations above 0.6 arcsec are predicted. Monte Carlo simulations have been used to estimate the numbers of stars around which planets of various masses would be detected at various projected distances, broadly corresponding to  $2M_J$  at ages of 1 Gyr and less than  $1M_J$  for young objects with ages less than 300 Myr (Krist et al., 2007, Table 1).

MIRI, the mid-infrared camera, provides coronagraphic imaging from 5–28  $\mu\text{m}$  using three four-quadrant phase-mask coronagraphs and a classical Lyot coronagraph. Each has its own wavelength filter (at 10.6, 11.4, 15.5, and 23  $\mu\text{m}$  respectively), with the coronagraphic stops deposited onto the filters (Boccaletti et al., 2005; Baudoz et al., 2006). Contrasts of  $10^4$ – $10^5$  are predicted between 0.5–1.0 arcsec, corresponding to the signal of a  $5M_J$  planet at an age of 1 Gyr.

The other two instruments are the Near-Infrared Spectrograph (NIRSpec), and the Near Infrared Imager and Slitless Spectrograph (NISISS). The latter, which replaced the earlier

Tunable Filter Imager (TFI), is associated with the telescope's Fine Guidance Sensor (FGS), and includes exoplanet detection, characterisation, and transit spectroscopy, as part of its goals.

**WFIRST** WFIRST (\$5.9.5) comprises a 2.4-m telescope equipped with a coronagraph for direct imaging. Greco & Burrows (2015) assessed its capabilities for exoplanet imaging, finding that the probability of Jupiter-mass planet detection is low for a blind search, but significantly improved with orbital parameter constraints from radial velocity campaigns and with Gaia.

**SPICA** The planned Japanese mission SPICA is described in Section 6.8.4.

### 7.7.3 Concepts for future space imaging missions

HST, Spitzer, and JWST do not have the angular resolution, nor were they designed, for the task of exoplanet imaging. More targeted ideas nevertheless began to emerge already in the 1970s (box, page 351). Primarily addressing high-resolution imaging, concepts frequently include low-resolution spectroscopy for simultaneous atmospheric characterisation.

Requirements for high angular resolution imaging developed into the infrared nulling interferometry concepts which formed the basis both of ESA's Darwin study, and of NASA's original Terrestrial Planet Finder (TPF) study, which were carried out over the period 1995–2005. In both cases, several large-aperture telescopes would fly in formation, and their light combined in a central hub using precisely controlled path delays. In both concepts, direct detection in the infrared would be accompanied by low-resolution spectroscopy.

The prospect of a realistic search for life on terrestrial exoplanets lay at the foundation of both projects. Their goals were the detection of exo-Earths, their physical and chemical characterisation, and the identification of possible biosignatures in their atmospheres.

**Search space for exo-Earths** Basing the search for life on the premises of organic chemistry, there are a number of arguments that have been used to constrain the search space. While these arguments are possibly incorrect, they serve as a basis for discussion and proceed broadly as follows (§11.7).

If life requires liquid water, then the search for life should focus on the habitable zone in which liquid water is present on the planet's surface or, more strictly, on the continuously habitable zone in which liquid water could have existed over billions of years as the star evolved in luminosity on the main sequence. The precise boundary of such a habitable zone, in terms of semi-major axis, eccentricity, albedo, greenhouse effect, and others is uncertain. Accordingly, a primary search zone can be considered to extend from 0.9–1.1 au, with a desirable search zone from 0.7–2 au. For host star spectral types other than solar, the habitable zone scales as  $L_*^{1/2}$ .

Plate tectonic activity has been considered necessary to sequester and recycle  $\text{CO}_2$  (§12.3.5). The minimum planetary mass required to sustain tectonic motion is unknown, so therefore is the minimum diameter of a terrestrial exoplanet, and its

**Early ideas for exoplanet imaging from space:** Bonneau et al. (1975) considered Lyot filtering to decrease the brightness of the Airy rings in what was then the Large Space Telescope, while KenKnight (1977) suggested an analogue of phase-contrast microscopy to attenuate scattered light arising from the imperfect figure of a 2-m space telescope. Elliot (1978) proposed a space telescope in an orbit yielding a stationary lunar occultation of any star lasting two hours, using the black limb of the moon as an occulting edge to reduce the background light from the planet's star.

Bracewell (1978) and Bracewell & MacPhie (1979) noted that with Sun/Jupiter temperatures of 6000 K and 128 K, detection of thermal emission in the Rayleigh–Jeans regime longward of  $\sim 20 \mu\text{m}$  (where the emission from the planet is strongest) would result in a factor of  $10^5$  improvement in contrast. They also introduced the principle of nulling interferometry to enhance the planet/star signal.

Ideas for improved space missions (Angel et al., 1986; Korechoff et al., 1994) or balloon experiments above altitudes of 30 km (Terrile & Ftaclas, 1997) were subsequently developed. It was shown that multi-element arrays can provide a deep central null with high-resolution fringes that can be used for mapping. These were predicted to yield full constructive interference for a close-in planet even in the presence of a resolved stellar disk or dust cloud (Angel & Woolf, 1996, 1997; Woolf & Angel, 1997).

Nulling interferometry remained as baseline for TPF-I and Darwin, although different approaches, such as pupil apodisation (Nisenson & Papaliolios, 2001), and pupil densification, for imaging (Riaud et al., 2002) or spectroscopy (Matsuo et al., 2016), have been suggested as alternatives.

associated reflecting area. A minimum has been proposed at around  $R_p = 0.4R_\oplus$ . Planets with  $M_p > 10M_\oplus$ , i.e.  $R_p > 2R_\oplus$  for rocky planets and  $R_p > 3R_\oplus$  for water planets, would likely accrete hydrogen and evolve into gas giants.

Exoplanet surface albedos are also expected to vary widely, from  $A_B = 0.05$  for an ocean or a Moon-like surface to values of 0.4 or higher. But for terrestrial planets massive enough to retain an atmosphere, the total albedo is likely to be dominated by atmospheric scattering, and albedos towards the upper range are to be expected.

**Optical versus infrared: technical** As the TPF and Darwin studies developed, there was a continuing debate about the relative merits of detecting and characterising Earth-like planets in the visible stellar light reflected by the planet, or in the thermal infrared where the planet/star contrast is greatly improved. The technical solution to the former has generally been considered to be via coronagraphy associated with a single telescope (although coronagraphy could equally well be implemented with an interferometric array), with the technical solution in the infrared being generally associated with the concept of a free-flying interferometer (e.g. Beckwith, 2008).

There has been no definitive resolution of this issue. Technologically, various advantages accrue from searches at visible wavelengths. For a given angular resolution  $\lambda/D$  the required aperture scales with  $\lambda$ , resulting in mirror sizes in the optical of order 6–12 m, which are still substantial but perhaps more tractable than interferometric baselines in the thermal infrared a factor three larger, i.e. at around 20–40 m.

At visible wavelengths, the telescope does not contribute to the radiation background, meaning that the telescope can be operated at around 300 K, offering significant engineering ad-

vantages over a thermal infrared instrument which would need to be cooled to  $\sim 40$  K. In the thermal infrared, background radiation from solar system zodiacal light is a further complication; the emission from solar system dust (arising from comets and asteroids) itself peaks around 10–20  $\mu\text{m}$ . If the instrument could be placed at 4–5 au from the Sun, the corresponding zodiacal background contribution would be reduced by about 100 (Léger et al., 1998; Landgraf & Jehn, 2001; Gurfil et al., 2002).

Although a visible light system would be much smaller than a comparable infrared interferometer, major advances in optical mirror technology would still be required. The TPF studies concluded that the mirrors would need to be ‘ultra-smooth’ to minimise scattered light, and that active optics would be needed to maintain low and mid-spatial frequency mirror structure. Infrared interferometry would require large boom technology or formation flying, with separation accuracies of around 0.01 m and short internal delay lines.

**Optical versus infrared: scientific** Scientifically, there are arguments for both spectral regions (e.g. Schneider, 2002b,a; Arnold et al., 2002; Schneider, 2003).

In the visible, spectral features and associated planetary diagnostics are numerous (Figure 11.44). They include the absorption bands of  $\text{H}_2\text{O}$ ,  $\text{O}_2$ , and  $\text{O}_3$  (including the Chappuis bands at 520–580 nm); Rayleigh scattering from the columnar abundance of gases and clouds; vegetation ‘red edge’ (at 725 nm for terrestrial vegetation); overall colour (e.g. whether similar to Venus, Earth, Mars or Jupiter); brightness (indicating planet size and albedo); brightness variations (indicating rotation rate, weather patterns, and the presence of oceans or land masses); and polarisation (characterising the molecular atmosphere). Measured values can further be used to infer properties such as temperature, diameter, mass, surface gravity, and atmospheric pressure. If the planet more closely resembles the primitive Earth (Figure 12.10), then  $\text{CH}_4$  and  $\text{CO}_2$  may also be significant.

A reference optical wavelength range could be set at 500–800 nm, although extensions to 300 nm would include the Huggins  $\text{O}_3$  bands at 330 nm, while extension to 1.3  $\mu\text{m}$  would include additional  $\text{H}_2\text{O}$  and  $\text{CO}_2$  bands.

In the infrared, the important molecular bands of  $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , and  $\text{O}_3$  have been considered as particularly valuable diagnostics for the presence of life (§11.8.5). However, while the  $\text{O}_3$  band at 9.6  $\mu\text{m}$  may be the signature of an  $\text{O}_2$ -rich atmosphere produced by photosynthetic life forms,  $\text{O}_2$ , and hence  $\text{O}_3$ , may also be built up without life from the photolysis of  $\text{H}_2\text{O}$  and  $\text{CO}_2$ . The analysis of Selsis et al. (2002) suggests that, while the detection of  $\text{O}_2$  may provide only an ambiguous indicator of life, the triple signature of  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , and  $\text{O}_3$  may provide a robust discriminator.

In either case, a resolution  $R \sim 70$  is necessary to quantify the presence and equivalent widths of the various features.

**Achievable signal-to-noise** An order-of-magnitude estimate of the achievable signal-to-noise for exoplanet detection has been given by Quirrenbach (2005, Section 3.5), which underlines its challenging nature. For a G star of  $V = 5$  mag, an Earth in the habitable zone with  $V = 30$  mag over the range 400–800 nm contributes  $N = 100\epsilon A$  photons  $\text{hr}^{-1}$ , where  $\epsilon$  is the total detection efficiency and  $A$  is the collecting area in  $\text{m}^2$ .

Assuming  $\epsilon = 5\%$  and  $A = 3.5 \times 7 \text{ m}^2$ , then  $N = 100$  photons  $\text{hr}^{-1}$ . If photon noise dominates both speckle and detector noise, then for  $S/N = 7$ , the detection times for different spectral features (Rayleigh scattering with  $R = 3$ , vegetation red edge,  $\text{CH}_4$ ,  $\text{H}_2\text{O}$ ) range from 2–80 h. The detection of albedo variations of 30% at the same  $S/N$  requires  $\sim 400$  h.

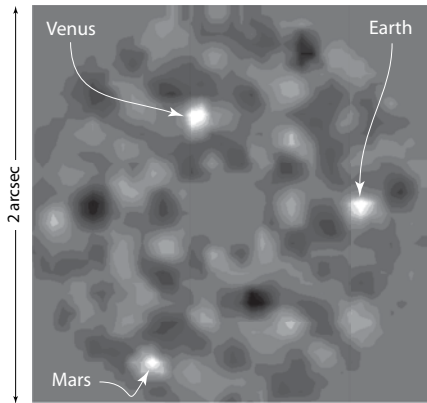


Figure 7.14: Simulation of a 60-h exposure of the original Darwin interferometer, with six 1.5-m telescopes in a 1 au orbit and 50-m baseline observing between 6–17  $\mu\text{m}$ . It covers a  $2 \times 2$  arcsec<sup>2</sup> field, and simulates a solar-type star at 10 pc, with solar-level zodiacal dust, and three inner planets yielding terrestrial-level flux at locations corresponding to Venus, Earth and Mars. The stellar light, at the image centre, has been nulled.

**Darwin** ESA embarked on the Darwin Infrared Space Interferometer study as a high-priority but longer-term programme in 1996. It was proposed as a nulling interferometer, operating in the infrared, which could search for Earth-like planets around 100–200 stars out to distances of 15–20 pc using direct imaging, and analyse their atmospheres for the chemical signature of life (Léger et al., 1996; Mariotti et al., 1997; Mennesson & Mariotti, 1997; Léger et al., 1998; Fridlund, 2000; Fridlund et al., 2003; Fridlund, 2004; Mennesson et al., 2005; Ollivier, 2007; Cockell et al., 2009a,b).

It was originally conceived as a set of eight spacecraft, placed at L2, with six free-flying 1.5-m class telescopes, one beam combination unit, and one communication unit. It would be passively-cooled to 40 K, and provide baselines up to 50 m. It would operate between 6–17  $\mu\text{m}$  to cover spectral lines including H<sub>2</sub>O, CH<sub>4</sub>, O<sub>3</sub> and CO<sub>2</sub> (Figure 7.14).

Later studies adopted a configuration employing four telescopes separated by up to 50–100 m operated in a ‘dual-Bracewell’ configuration, requiring a dual Soyuz-Fregat launch, and with a target launch date of 2015. The mission scheduled a detection phase of two years, and a spectroscopic phase of three years.

Table 7.4 summarises estimated Darwin integration times for various stellar types, using a 90% confidence level based on three observations. Two  $\pm 45^\circ$  sky caps near the ecliptic poles are inaccessible. The study identified some 500 F5–K9 stars out to 25 pc, of which some 285 are single. There are 2–5 G0V–G2V stars within 10 pc, and 21 single, non-variable G0V–G4V stars within 15 pc. Darwin targeted a survey of all 285 single FGK stars out to 25 pc, with a spectrum of 30 planets in the case of a planet prevalence of  $\sim 10\%$ .

Table 7.4: Integration times for Darwin for the detection of Earth-like planets at  $S/N = 5$ , and spectroscopy at  $S/N = 7$  in the faintest part of the spectrum (in hours). Assumptions are: spectral range 6–17  $\mu\text{m}$ ; resolving power  $R = 20$ ;  $A_{\text{total}} = 40 \text{ m}^2$ ;  $T_{\text{optics}} = 40 \text{ K}$ ; planetary  $T_{\text{eff}} = 265 \text{ K}$  (signal  $\propto T_{\text{eff}}^4$ );  $R = R_{\oplus}$ ; zodiacal dust =  $10 \times$  inner solar system; Si–As detectors.

Stellar type	10 pc	20 pc	30 pc
G2V	18–33	28–54	109–173
G5V	12–22	27–46	105–166
K2V	4–9	26–37	104–157
K5V	4–6	26–35	249–155

**Terrestrial Planet Finder** NASA’s Terrestrial Planet Finder (TPF) advanced in parallel with the Darwin study. TPF was conceived to take the form of a coronagraph at visible wavelengths, or a 75–100-m baseline interferometer in the infrared (Beichman, 1996; Thronson, 1997; Beichman, 1998, 2003; Lawson et al., 2006, 2008).

In May 2002, two concepts were selected for further evaluation: an infrared interferometer (multiple small telescopes on a fixed structure or on separated spacecraft flying in precision formation and utilising nulling), and a visible light coronagraph (a large optical telescope, with a mirror three to four times larger and at least 10 times more precise in wave-front error than HST).

In April 2004, NASA announced that it would embark on a  $6 \times 3.5 \text{ m}^2$  visual coronagraph in 2014, designated TPF-C. It would operate over 0.6–1.06  $\mu\text{m}$ , and would target a full search of 32 nearby stars and an incomplete search for 80–130 stars. For the detection of ozone at distances of 15 pc and  $S/N \sim 25$ , apertures of about  $40 \text{ m}^2$ , and observing times of 2–8 weeks per object, were indicated. A free-flying interferometer, with ESA, could then be considered before 2020 (designated TPF-I).

Design work continued, with three concepts representing a possibly phased implementation (TPF-C, an external occulter TPF-O, and TPF-I) being considered (Traub et al., 2007). TPF-C was re-baselined as a probe-class mission in 2006 with less ambitious objectives, and in which context concepts such as ACCESS (Trauger et al., 2008), EPIC (Clampin, 2007), and PECO (Guyon et al., 2008) were studied.

**Overall comparison** Table 7.5 indicates the signal-to-noise that could be expected from a 24 h observation of an Earth at 10 pc, in the optical and near-infrared, for various large telescope concepts. A 100-m aperture, and one sited in the Antarctic, are included for performance comparison, although neither is currently under serious consideration. Even if Earths at distances as close as 10 pc exist, detection and spectroscopy will be challenging, even with 100-m apertures or space interferometers.

**Precursors or alternatives** The 2000 Decadal Survey Committee (McKee & Taylor, 2000) qualified its endorsement of the TPF mission with the condition that the abundance of Earth-size planets be determined prior to any start. In addition, issues of solar system zodiacal emission, and the effects of extrasolar

Table 7.5: Detection capabilities for an Earth-type planet at 10 pc, from Angel (2003a), assuming  $\Delta\theta = 0.1$  arcsec,  $t_{\text{int}} = 24$  h,  $QE = 0.2$ ,  $\Delta\lambda/\lambda = 0.2$ . Mode N corresponds to a nulling system, C to a coronagraph. Ground-based results assume fast atmospheric correction, and that long-term averaging is realistic. Optical spectroscopy only becomes feasible for  $D \sim 100$  m. An Antarctic 100-m telescope gives comparable signal-to-noise to Darwin/TPF at 11  $\mu\text{m}$ , although  $\text{O}_3$  at 9.6  $\mu\text{m}$  and  $\text{CO}_2$  at 15  $\mu\text{m}$  are inaccessible due to atmospheric opacity.

Telescope	$D$ (m)	$\lambda$ ( $\mu\text{m}$ )	Mode	S/N
Darwin/TPF-I	$4 \times 2$	11	N	8
TPF-C	3.5	0.5	C	11
"	7	0.8	C	5–34
Antarctic	21	11	N	0.5
"		0.8	C	6
TMT, GMT	30	11	N	0.3
"		0.8	C	4
OWL	100	11	C	4
"		0.8	C	46
Antarctic OWL	100	11	C	17
"		0.8	C	90

zodiacal emission on exoplanet detection probabilities (Angel, 1998), meant that precursor missions with less-ambitious goals were also proposed (Malbet et al., 1995).

Many ideas for technology precursors or replacements for TPF were subsequently put forward to NASA, typically involving 2-m class telescopes with combinations of adaptive wavefront correction, coronagraphs and apodisation, or larger interferometers and free-flying external occulters or starshades.

These included, lexically, ACCESS (Trauger et al., 2008); ATLAST (Postman et al., 2009; Brandt & Spiegel, 2014) Big Balloon Exoplanet Nulling Interferometer (BigBENI, Lyon et al., 2012); BOSS (Copi & Starkman, 2000); Eclipse (Trauger, 2007); EPIC (Clampin, 2007); ESPI (Lyon et al., 2003); EXCEDE (Belikov et al., 2012; Guyon et al., 2012b); ExPO (Gezari et al., 2003); FKSI (Danchi et al., 2003; Danchi & Lopez, 2007; Barry et al., 2008a; Danchi et al., 2008); OPD (Mennesson et al., 2003); PECO (Guyon et al., 2008); TOPS (Guyon et al., 2006a, 2007); 4m-TPF (Brown et al., 2003); and UMBRAS (Schultz et al., 2003).

NASA's Space Interferometry Mission, SIM, designed for optical astrometry at  $\mu\text{as}$ -level with maximum baselines of  $\sim 10$  m, was also viewed as a technological precursor for TPF, capable of imaging and nulling albeit at much lower angular resolution (Böker & Allen, 1999).

An interferometer precursor for Darwin, PEGASE, proposed 3 free-flying satellites comprising two 0.4-m siderostats and one beam combiner (Ollivier et al., 2006, 2009). A precursor coronagraphic mission, SEE-COAST (Super-Earth Explorer Coronagraphic Off Axis Space Telescope), with polarimetry and spectroscopy, was (unsuccessfully) submitted to ESA's Cosmic Vision programme in 2007 (Schneider et al., 2006a, 2009b), and subsequently as SPICES, the Spectro-Polarimetric Imaging and Characterisation of Exoplanetary Systems (Boccaletti et al., 2012; Maire et al., 2012a,b). GENIE was proposed as a nulling interferometer for VLTI, to test the Darwin technology (den Hartog et al., 2006; Gondoin et al., 2008).

A mission assessment framework for the detection and characterisation of Earth-like planets in the habitable zone was described by Savransky et al. (2010a). Trade-offs have been further evaluated by Brown (2015a).

**Current status** After decade-long studies, the Darwin and TPF concepts *per se* were no longer under active consideration in the ESA and NASA programmes. Contributing factors were their technical challenges and costs. Final system performances gave only modest signal-to-noise for the detection of Earth-like planets at 10 pc, an objective itself resting, at the time, on the fragile assumption that such planets exist. At the same time, more rigorous performance simulations, partly based on Kepler occurrence statistics, continue to be made (Kammerer & Quanz, 2018).

In the 2010 US Decadal Survey (McKee & Taylor, 2000), new technical studies in the framework of the New Worlds Observer (§7.4.4) were given high priority.

In 2016, NASA embarked on studies for its next 'flagship' telescope, expected to conclude in 2019 for consideration in the 2020 Astrophysics Decadal Survey, and targeting launch around 2035. Of these, two studies are focused on exoplanet imaging missions:

*HabEx*: the Habitable Exoplanet Imaging Mission is a concept for a mission to directly image planetary systems around Sun-like stars, employing a large ( $> 3.5$  m), stable, and diffraction-limited optical space telescope. Its main goal is to directly image Earth-like exoplanets (with a coronagraph or star shade), and characterise their atmospheric content through spectroscopy in molecules such as  $\text{H}_2\text{O}$ ,  $\text{O}_2$ , and  $\text{O}_3$  (e.g. Mennesson et al., 2016; Deming & Seager, 2017).

*LUVVOIR*: the Large UV/Optical/IR Surveyor is another multi-wavelength space observatory concept, targeting an 8–16-m primary mirror, and also focusing on exoplanet imaging and spectroscopy (Crooke et al., 2016).

## 7.8 Other imaging concepts

Perhaps more than any other of exoplanet research, major advances in exoplanet imaging, and especially resolved imaging, will require substantial technological advances. This section makes reference to some of the longer-term prospects that have been put forward.

Although prospects for spatially resolved imaging are generally considered as rather remote, first steps in this direction are, nonetheless, represented by the observed changes in high-resolution transmission spectra over the transit (§11.4.2), and time-varying atmospheric structures inferred from orbital phase curves (§6.14.8).

### 7.8.1 Medium-term prospects

**Intensity interferometry** In contrast to amplitude interferometry (Section 7.6.5), *intensity interferometry* (e.g. Brown & Twiss, 1958) aims at measuring the *second-order* coherence of light, i.e., intensity, rather than amplitude or phase. This is achieved by measuring temporal correlations of photon arrival times recorded at different telescopes. The technique is largely insensitive to

atmospheric turbulence, permitting long baselines and observations at short (optical) wavelength, although demanding large and well-distributed telescopes.

However, since realistic time resolutions are much longer than typical optical coherence times for broadband light, any intensity-fluctuation signal is averaged over many coherence times. As a result, reliable determination of the smeared-out signal requires very good photon statistics. The first intensity correlation measurements since the historical experiments of Brown & Twiss were reported by Guerin et al. (2017) for the bright stars,  $\alpha$  Boo,  $\alpha$  CMi, and HD 62509 ( $\beta$  Gem).

**Cherenkov Telescope Array** The Cherenkov Telescope Array (CTA) is a  $\gamma$ -ray observatory with some 100 telescopes, distributed over a few sq. km in both northern and southern hemispheres, and a total light-collecting area of some 10 000 m<sup>2</sup> (Acharya et al., 2013). Among its foreseen uses is as an intensity interferometer, correlating intensity fluctuations between telescope pairs across different baselines, applying time shifts in software to track sources across the sky (Dravins et al., 2012, 2013; Dravins, 2014; Dravins et al., 2015; Matthews et al., 2017; Tan & Kurtz, 2017). Since the signals are copied electronically (with no optical connection between telescopes), there is no further loss when forming additional baselines between any pairs of telescopes. Experimental verification of this concept has been demonstrated (Dravins et al., 2015), resulting in the first diffraction-limited images obtained from an optical array linked only by electronic software.

Dravins et al. (2015) simulated the transit of a  $1M_J$  exoplanet, with a Saturn-like moon and four Earth-sized ‘Galilean’ moons, across the star Sirius ( $d = 2.6$  pc). The star serves as a copious source of photons such that, away from the stellar limb, only the amplitude of the Fourier transform of the exoplanet image is measured. The full CTA resolution of  $\sim 50 \mu\text{s}$  compares favourably with the planet diameter of  $350 \mu\text{s}$ , and the stellar diameter of  $6000 \mu\text{s}$  (Figure 7.15). Accordingly, while spatially resolving an exoplanet disk in reflected light may remain problematic for some time, imaging of its dark silhouette transiting a stellar disk might be possible somewhat sooner (Strekalov et al., 2013b, 2014).

**Fresnel imaging** Visible wavelength interferometers are currently limited to a small number of apertures (up to eight with VLT), limiting the field/resolution ratio in reconstructed images. A Fresnel array aims to improve imaging capabilities by the recombination of a very large number of beams from basic rectangular-hole apertures. The array acts as a Fresnel plate by directly focusing the light (and combining the beams) into a point spread function of high dynamic range by diffraction, without the need for reflective or refractive elements.

The *Fresnel imager* is a concept for a large field, large aperture, high dynamic range, lightweight imager capable of observation between the ultraviolet and mid-infrared (Koechlin et al., 2005, 2009; Rivet et al., 2011; Koechlin et al., 2011, 2012, 2014; Roux & Koechlin, 2016; Koechlin et al., 2017). Due to the long focal lengths, this requires formation-flying of two spacecraft.

First sky images using a  $200 \times 200 \text{ mm}^2$  Fresnel array have been reported (Koechlin et al., 2011, 2012). The array is a  $50 \mu\text{m}$  thick opaque foil comprising 250 000 specially shaped voids, corresponding to 696 Fresnel zones. High-contrast diffraction-limited images of two multiple stars and Saturn at the OCA

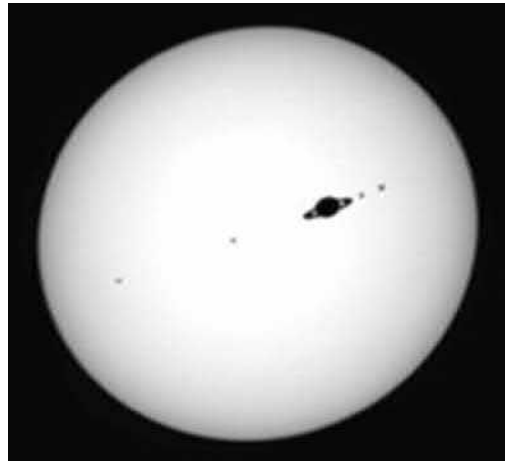


Figure 7.15: Simulation of microarcsec optical imaging with intensity interferometry, showing a hypothetical exoplanet transit across Sirius ( $R_\star = 1.7R_\odot$ ,  $d = 2.6$  pc,  $\theta = 6$  mas), assuming a planet of Jupiter size and oblateness ( $2R_p = 350 \mu\text{s}$ ), with Saturn-type rings and four Earth-size moons. With a CTA configuration spanning 2 km, a  $50 \mu\text{s}$  resolution provides more than 100 pixels across the stellar disk. From Dravins et al. (2015, Figure 9), reproduced with permission © ESO.

0.7-m refractor achieved a field of view of 500 arcsec, a resolution 0.8 arcsec at 800 nm, and a dynamic range  $> 10^5$ .

### 7.8.2 Future prospects: resolved imaging

Within NASA's Origins Program of the early 1990s, HST, Spitzer and others were referred to as ‘precursor missions’. SIM and JWST were referred to as ‘First Generation Missions’, employing either large, lightweight optics or collections of small telescopes providing images equivalent to those obtainable with a single, much larger instrument. The first generation missions were to serve as technological stepping stones to the second generation missions, including Terrestrial Planet Finder (TPF), and the third generation missions, including Life Finder and Planet Imager. These illustrate the complexity involved in going beyond TPF/Darwin.

**Life Finder** TPF targeted the detection of the nearest planetary systems, with low-quality spectra foreseen as a realistic by-product. Life Finder was only to have been considered after the Darwin/TPF results became available, and once  $\text{O}_2$  or  $\text{O}_3$  had been discovered. Life Finder would then target confirmation of the presence of life, searching for an atmosphere significantly out of chemical equilibrium, for example through the simultaneous presence of  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , and  $\text{O}_3$ .

Some pointers to the technology requirements and complexity of Life Finder have been described by Woolf (2001), who considered that the light collecting area of Life Finder would have to be substantially larger than that of TPF, and adopted targets of  $500\text{--}5000 \text{ m}^2$ . One

of the primary technical challenges would be to produce such a collecting area at affordable cost and mass. According to this study, a ‘mini-Life Finder’ might be a  $50 \times 10 \text{ m}^2$  telescope, with 12 segments of  $8.3 \times 5 \text{ m}^2$ , made of  $5 \text{ kg m}^{-2}$  glass, piezo-electric controlled adaptive optics, and total mass of about  $10^4 \text{ kg}$ .

To detect the  $7.6 \mu\text{m}$   $\text{CH}_4$  feature, the required collecting area rises from  $220 \text{ m}^2$  (four or five 8-m telescopes) for a planet at 3.5 pc, to  $4000 \text{ m}^2$  (eighty 8-m telescopes) at 15 pc. An outline technology development plan for Life Finder indicated costs as  $\gg \$2$  billion.

**Planet Imager** The imaging of planetary systems referred to so far in this chapter concerns exoplanet detection in which the planet appears only as a point source. Resolving the surface of a planet is, in contrast, a far future goal requiring substantial technology development that is not yet even in planning. Much longer baselines, from tens to hundreds of km, would be needed. Formation flying will require technology development well beyond that of Darwin/TPF, including complex control systems, ranging and metrology, wavefront sensing, optical control and on-board computing.

A plausible Planet Imager would demand 50–100 Life Finder telescopes operating in an interferometric array. Woolf (2001) concluded: ‘*the scientific benefit from this monstrously difficult task does not seem commensurate with the difficulty*’.

Bender & Stebbins (1996) also undertook a partial design of a separated spacecraft interferometer which could achieve visible light images with  $10 \times 10$  resolution elements across an Earth-like planet at 10 pc. This called for 15–25 telescopes of 10-m aperture, spread over 200 km baselines. Reaching  $100 \times 100$  resolution elements would require 150–200 spacecraft distributed over 2000 km baselines, and an observation time of 10 years per planet. The effects of planetary rotation on the time variability of the spectral features complicates the imaging task, while more erratic time variability (climatic, cloud coverage, etc.) will further exacerbate any imaging attempts. They noted that the resources identified would dwarf those of the Apollo or Space Station programmes, concluding that it was ‘*difficult to see how such a programme could be justified*’.

**Hypertelescopes** Resolved imaging using ‘hypertelescopes’ on Earth and in space have also been considered in Europe (Labeyrie, 1996; Pedretti et al., 2000; Labeyrie, 2002; Riaud et al., 2002; Gillet et al., 2003; Labeyrie, 2003; Labeyrie et al., 2003; Labeyrie & Le Coroller, 2004; Le Coroller et al., 2004; Martinache & Lardière, 2006; Reynaud & Delage, 2007; Aime, 2008; Bouyeron et al., 2010; Labeyrie, 2013).

The basic hypertelescope design is based on a (dilute, Fizeau) interferometric array of smaller apertures, with a ‘densified’ exit pupil. This means that the exit pupil has sub-pupils with a larger relative size than the corresponding sub-apertures in the entrance pupil, and thereby serving to increase sensitivity at the expense of field of view (Pedretti et al., 2000, their figure 1). [A similar approach for space-based *densified pupil spectroscopy* is detailed by Matsuo et al. (2016, see their Figure 1).] Numerous widely-spaced mirrors give the usual difficulty of adjusting and phasing the interferometers.

Riaud et al. (2002) evaluated the performance of an infrared hypertelescope (comprising  $37 \times 0.6\text{-m}$  apertures over an 80 m baseline) combined with a phase-mask coronagraph to yield attenuations of  $10^{-8}$ . Simulations of the 389 Hipparcos M5–F0 stars out to 25 pc, and including the contributions from zodiacal and exozodiacal background, yielded 10-h snapshots in which an Earth-like planet was detectable around 73% of the stars. Gains of 20–30 with respect to a simple Bracewell-type nulling interferometer were reported.

In space, a hypertelescope would comprise a flotilla of dozens or hundreds of small elements deployed in the form of a large dilute mosaic mirror. Pointing would be achieved by globally rotating the array using solar sails. Somewhat paralleling the conclusions of the Life Finder and Planet Imager studies, an exo-Earth discoverer would require 100–1000 m baselines, while an exo-Earth imager would require baselines of order 150 km. For the latter, a 30-min exposure employing  $150 \times 3\text{-m}$  apertures could detect ‘green’ spots similar to the Amazon basin on a planet at 3 pc (Labeyrie, 2002).

**Carlina** A simplified optical and mechanical architecture, *Carlina*, is under development at the Observatoire de Haute Provence (FRA). It consists of an optical interferometer, analogous to a diluted version of the Arecibo radio telescope (Figure 7.16). Above the array of fixed co-spherical mirror segments, a helium balloon, or suspended cables, carries a ‘floating’ gondola with focal optics, metrology, and servo loop.

Fringes for an 18-m baseline prototype were reported in 2004 (Le Coroller et al., 2004, 2012a), with a three 0.25-m 10.5-m baseline prototype subsequently constructed (Le Coroller et al., 2012b), and fringes on Deneb demonstrated (Le Coroller et al., 2015). The Ubaye hypertelescope, with a fixed spherical metamirror of 57-m effective aperture, is under consideration in the Moutière Valley south-east of Grenoble, exploiting its smooth glaciated topography (Labeyrie, 2013).

**Microlensed-based imaging** The possibility of exoplanet imaging exploiting gravitational lensing by the Sun (or at other planetary solar system foci) was described in Section 5.7. A related concept of femtolens imaging, proposed for resolving the ‘central engine’ of quasars, is to position a moving spacecraft at an appropriate location in the solar system to exploit the lensing of a selected nearby dwarf star (Gould & Gaudi, 1997).

### 7.8.3 Planetary radar

Many advances have been made in understanding the (near-)surface properties of solar system objects using *planetary radar*. This involves the active transmission of modulated radio waves, and the detection of the reflected energy. This has mostly been from Earth-based systems, but also from spaceborne transmitters and receivers (e.g. Ostro, 1993; Muhleman et al., 1995).

Signals reflected from the Moon were first recorded in 1946, from Venus in the early 1960s, and from the



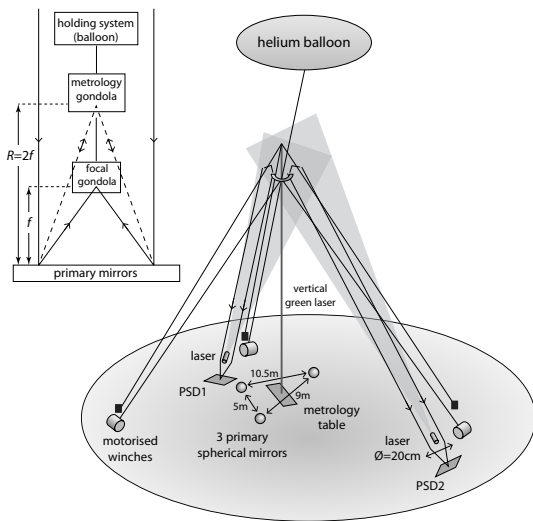


Figure 7.16: Carlina interferometer schematic. Three primary mirrors surround the metrology table. The convex metrology mirror is attached and passively positioned via a gondola, with a He balloon keeping the cables (black lines) under tension, and stabilised by motorised winches. Displacements are measured by lasers and corner cubes. The inset shows the four main systems: primary mirrors, focal gondola, metrology gondola, and the holding system. Solid lines show the stellar light, and dashed lines show the coherencing laser beams. From Le Coroller et al. (2012a, Figures 1–2), reproduced with permission © ESO.

moons of Jupiter and the rings of Saturn in the mid-1970s. The Saturnian rings and its moon Titan are the most distant objects probed by the largest ground-based facility at Arecibo: Titan imaging calls for a one-way light travel time of 67 min, an antenna of 73 000 m<sup>2</sup>, and an EIRP (equivalent isotropic radiated power) of 20 TW, using a transmitter of 1 MW and antenna gain of 73 db.

**Solar system insights** Radar has provided detailed information about the geological and dynamical properties of the inner planets, natural satellites, asteroids, and comets. Topographic maps can be reconstructed from precise time delays to a structured surface, allowing for morphological studies of mountain ranges, surface slopes, fault lines, and craters, as well as knowledge of the object's spin state. Electrical reflectivity carries information about surface densities and, to some extent, the chemistry to depths of  $\sim 10\lambda$ , enabling limited geological mapping. Radar also allows studies of the atmospheric and ionospheric layers, and the interplanetary medium.

Studies include the surfaces of the Moon (e.g. Thompson, 1970; Margot et al., 1999; Kesaraju et al., 2017; Vierinen et al., 2017), Mercury (Anderson et al., 1991; Butler et al., 1993; Harmon et al., 2007; Harmon, 2007), Venus (Burns & Campbell, 1985; Barsukov et al., 1986), Mars (Downs et al., 1975; Harmon & Ostro, 1985; Roth et al., 1989; Harmon et al., 1999, 2012; Harmon & Nolan, 2017), Jupiter's moons (Goldstein & Green, 1980; Eshleman, 1986; Ostro & Shoemaker, 1990; Ostro et al., 1992; Heggy et al., 2017), Titan, from ground and Cassini (Campbell et al., 2003; Elachi et al., 2004; Black et al., 2011), asteroids (Ostro et al., 1991), and Saturn's rings (Goldstein et al., 1977). Radar also yields information on the scale of the solar system (Muhle-

man et al., 1962), planet rotation (Pettengill & Dyce, 1965), planetary ephemerides (Ash et al., 1967), and the solar oblateness and tests of general relativity (Shapiro, 1966; Pitjeva, 2005).

**Extension to exoplanets** Several authors have considered the use of Earth-launched radar as a probe of nearby exoplanets (Rzhiga, 1985; Williams, 1985; Scheffer, 2014). Accessible properties might include the planet's orbital elements, its mean radius, and its surface relief. To probe an Earth-size planet even around  $\alpha$  Cen, however, currently appears technologically implausible. Rzhiga (1985) invoked a 70-km antenna with a 2 TW transmitter. Williams (1985) considered an even more ambitious space interferometer. Scheffer (2014) distributed the required transmitter/receiver costs by proposing a transmitter  $\times 10^{15}$  more powerful than Arecibo, and a receiver  $\times 10^5$  more sensitive. These conclusions are not affected by the advent of the FAST 500-m single dish radio telescope (Li & Pan, 2016).

### 7.8.4 Gravitational wave signatures

The first observation of gravitational waves, announced by the LIGO/Virgo collaborations in 2016 (Abbott et al., 2016), and ESA's adoption of the LISA mission (Laser Interferometer Space Antenna) for launch in 2034, have opened a fundamentally new window on prospects for the characterisation of close-orbiting bodies.

Loosely associated with imaging techniques, there are at least three manifestations of orbiting exoplanets that are, in principle, related to gravitational wave signals: (i) gravitational waves emitted by a single star-planet system, (ii) the stochastic background signal due to all orbiting planets in the Galaxy and beyond, and (iii) the modulation in gravitational wave frequency of a compact white dwarf binary system orbited by a planet.

**Predictions** There are two related limits which preclude the detection of gravitational waves from any individual star-planet system, even with LISA: at the tidal disruption radius,  $\sim 1R_{\odot}$ , the corresponding frequency is  $\sim 0.3$  mHz, at the lowest end of the LISA band. Assuming the existence of such a system, the expected strain is  $h \sim 10^{-24} (d/1 \text{ kpc})^{-1}$  (cf. Nelemans et al., 2001, equation 3). Even if tens of thousands of cycles could be accumulated, a factor  $\sim 10^2$  increase in strain amplitude would still be some factor  $10^5$  below the LISA sensitivity.

The cumulative signal of all planets, in the Galaxy and beyond, with periods from a few hours to several years, will create a stochastic gravitational wave background. Ain et al. (2015) estimated that this would peak at  $\sim 10^{-5}$  Hz, with a maximum amplitude still below the LISA sensitivity.

A planet orbiting a compact double degenerate system, itself a strong gravitational wave source, would modulate the signal phase. Seto (2008) estimated that LISA could put limits  $\geq 4M_J$  on companions to 3000 Galactic white dwarf binaries.

### 7.8.5 Sub-diffraction limit imaging

In the context of the distant goal of achieving spatial resolution of an exoplanet surface, this section points to various *concepts* for achieving sub-diffraction limited angular resolution noted in the literature.

The diffraction limit inherent in conventional optics is explained by the Huygens–Fresnel principle of secondary wavefront generation and mutual interference,



and its mathematical formulation by Kirchhoff and others (e.g. Born & Wolf, 1999, Section 8.1). It is the diffraction limit which renders resolved exoplanet imaging so problematic for the foreseeable future.

**Superlenses** In the formulation of diffraction based on Maxwell's equations, evanescent waves carry structure at sub- $\lambda$  scales. In media with positive permittivity  $\epsilon$  and permeability  $\mu$ , these waves decay exponentially and transfer no energy to the image plane (e.g. Born & Wolf, 1999, Section 11.4.2).

Research in *metamaterials* (those engineered to provide properties not found in nature) is actively pursuing the development of negative refractive index materials in which both  $\epsilon$  and  $\mu$  are negative (Veselago, 1968). This has led to the conjecture of *superlenses* in which imaging at sub-wavelength resolution, by enhancing evanescent waves, might be feasible (Pendry, 2000; Ramakrishna, 2005; Nicolet & Zolla, 2011). Sub-diffraction limited resolution was reported at 1.06 GHz by Grbic & Eleftheriades (2004), and at 365 nm with  $\lambda/6$  resolution by Fang et al. (2005).

Practical relevance, notably for distant sources in which evanescent fields are absent, can be questioned (e.g. Lacki, 2015). Nevertheless, applied to astronomical telescope optics, May & Jennetti (2004) postulated that evanescent fields created by reflection off the primary could be amplified and modified to generate fields that sharpen the focus, hinting that techniques might be developed that will improve telescope resolution to below the diffraction limit. At radio wavelengths, super-resolution through the use of variable transmittance filters (Torraldo pupils) remains under consideration (Di Francia, 1952; Mugnai et al., 2003; Olmi et al., 2017).

**Photon cloning and heralding** Another approach which may offer sub-diffraction-limited prospects, albeit at the expense of efficiency, employs non-linear optical processes, specifically through photon cloning heralded by trigger events, especially those with an above average ratio of stimulated to spontaneous photons (Kellerer, 2014a,b; Kellerer & Ribak, 2016).

**Ghost imaging** The detection of intensity-correlation signatures of astronomical sources including exoplanets, in the quantum mechanical framework of *ghost imaging*, has also been noted (Strekalov et al., 2013a).

### 7.8.6 Desirable innovations

Achieving the long-term goal of resolving an exoplanet surface may be advanced by considering potentially 'disruptive' technologies which could significantly affect the design and operation of future telescopes and their instrumentation (Cunningham, 2009). Cunningham et al. (2012) considers such a list of desirable instrumental advances, irrespective of their current development status, and some considerations on how such technological advances might be catalysed.

For exoplanet imaging, this might include: deformable mirrors with 40000 actuators at a control rate of 3 kHz (compared to the present 1000 or so), with large stroke and minimal hysteresis; predictive adaptive optics, viz. predicting the next few ms of atmospheric turbulence or tomography, possibly through the use of 'helper telescopes' (Poyneer & Véran, 2008); improved ground-based infrared imagers and spectrometers

by OH line suppression with photonic devices (e.g. Allington-Smith & Bland-Hawthorn, 2010); idealised wavefront correction employing negative refractive index metamaterials; robust energy-sensitive photon detectors based on superconducting tunnel junctions (STJs, first proposed theoretically by Perryman et al., 1993); real-time atmospheric calibration; and much larger telescopes enabled by technologies such as the unfolding Fresnel mask (§7.8.1) or the hypertelescope (§7.8.2).

A number of advanced technologies for deformable mirrors have been proposed. Vertical-cavity surface-emitting laser systems (VCSELs) target the movement of a chemical-vapour deposition diamond membrane coated with a thin Al-Au film through radiation pressure, and appear capable of high-actuator density ( $128^2$  over  $6.4 \times 6.4 \text{ mm}^2$ ) without hysteresis (Riaud, 2012a). Magnetic-liquid deformable mirrors also show promise (e.g. Borra, 2012a; Lemmer et al., 2016).

## 7.9 Searches and surveys

The preceding sections have set out the techniques being directed at exoplanet imaging, and the variety of instruments, on ground and in space, that are being applied. Numerous imaging surveys are now being carried out, with the first detections of massive, young, self-luminous and wide-orbiting planets announced in 2005.

Nevertheless, there is little prospect of imaging an Earth-mass planet in an Earth-like orbit with current telescopes/instruments, and even imaging a Jupiter-like planet in a Jupiter-like orbit will be a major challenge.

**Survey yields** Due to the rapid fall-off in S/N with distance, due to the combined effects of inverse-square brightness decrease and reduced star-planet angular separation, the number of planets detectable with any given instrument is difficult to predict (although see §7.10.1). Garrett et al. (2017) give a 'depth-of-search' procedure to calculate expected exoplanet imaging yields that explicitly separates the effects of instrument performance from assumptions of planet distributions.

**Early programmes** After the first discoveries of exoplanets by indirect methods (around 1995), various direct imaging surveys were undertaken to search for substellar companion objects in the optical and near-infrared. As the instruments were not optimised for high-contrast imaging, the first surveys emphasised the search for brown dwarf and wide separation companions orbiting nearby stars (e.g. Schroeder et al., 2000; Gizis et al., 2001; Oppenheimer et al., 2001; Liu et al., 2002; McCarthy & Zuckerman, 2004; Lowrance et al., 2005; Carson et al., 2009; Bernat et al., 2010; Leconte et al., 2010b; Tanner et al., 2010).

Early results on the path to planet imaging included discovery of the brown dwarf GJ 229 B (Figure 7.17), imaged from the ground with adaptive optics, and from space by HST (Nakajima et al., 1995).

As examples, an infrared coronagraphic survey of 178 stars at Steward and Lick, with detection thresholds  $> 30M_J$  between 140–1200 au, and of 102 stars at

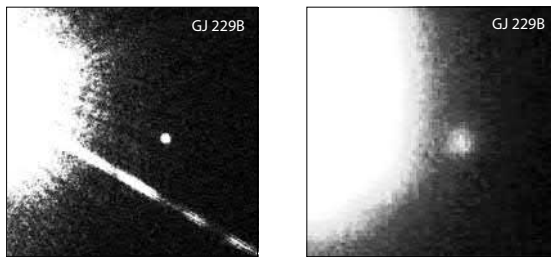


Figure 7.17: The brown dwarf GJ 229B imaged with an early adaptive optics/coronagraph system at the Palomar Observatory 60-inch telescope (left) and with HST (right). The brown dwarf is 7 arcsec from the bright star GJ 229A. The brightness ratio is  $\sim 5000$ , and the separation corresponds to that of Sun–Pluto. A Jupiter mass planet at a distance of 10 pc would be 14 times closer to its parent star, and roughly 200 000 times dimmer than GJ 229B. From Nakajima et al. (1995, Figure 1), by permission from Nature/Springer/Macmillan Ltd, ©1995.

Keck, with detection thresholds  $> 10M_J$  between 75–300 au, McCarthy & Zuckerman (2004) detected one brown dwarf companion and no planets. In a search using VLT–NACO for 28 stars, Masciadri et al. (2005) excluded the existence of  $5M_J$  planets beyond 14 au, and  $10M_J$  planets beyond 8.5 au for 50% of the targets.

With more performant adaptive optics, and new observing modes, later surveys of young stars started to probe fainter substellar companions down to the young gas-giant regime (e.g. Kasper et al., 2007; Lafrenière et al., 2007a; Nielsen et al., 2008; Metchev & Hillenbrand, 2009; Chauvin et al., 2010; Heinze et al., 2010b,a; Biller et al., 2011, 2013b; Rameau et al., 2013a; Yamamoto et al., 2013; Nielsen et al., 2013a; Wahhaj et al., 2013b).

**Searches around white dwarfs** Giant planets that survive the demise of their parent star are interesting candidates for direct imaging because of the favourable planet–white dwarf flux ratio. These programmes are considered, in the wider context of planetary systems around white dwarfs, in Section 8.9.

### 7.9.1 Searches with first-generation instruments

Included amongst these early imaging surveys were those undertaken with specific ‘first generation’ instruments, notably VLT–NACO, Gemini–NICI, Subaru–SEEDS, and LBT–LEECH (Figure 7.18).

Programmes expanded to cover various stellar types, such as high-mass stars (e.g. Janson et al., 2011a; Vigan et al., 2012b; Rameau et al., 2013b), young moving group stars (e.g. Evans et al., 2012), low-mass stars (e.g. PALMS, Bowler et al., 2012a,b, 2015, 2017b), binary stars (e.g. SPOTS, Thalmann et al., 2014a; Bonavita et al., 2016), as well as debris disk stars, and other nearby stars.

Methods for estimating discovery yields as a function of occurrence rates and schedule constraints have been variously described (e.g. Brown & Soummer, 2010; Crepp & Johnson, 2011).

**International Deep Planet Survey** Most imaging surveys have targeted young, nearby stars. For example, the International Deep Planet Survey (IDPS) sample has a median age of 120 Myr and a median distance of 45 pc (Galicher et al., 2016). The emphasis on young ages ensures that giant planets are bright enough in the near-infrared assuming evolutionary models like COND and DUSTY (Chabrier et al., 2000; Baraffe et al., 2003). Age indicators employed include Li, X-ray, ultraviolet emission, space velocity,  $H\alpha$ , and colour–magnitude diagrams (Zuckerman & Song, 2004).

The International Deep Planet Survey (IDPS, Vigan et al., 2012b; Galicher et al., 2016) resulted from the merger of two near-infrared imaging surveys that had been running for some 14 years, using Keck II, Gemini–North and South, and VLT, viz. a Keck adaptive optics search (Kaisler et al., 2003), and the (forerunner of the) international deep planet survey (Marois, 2010). Objectives include detection and spectroscopy of new exoplanets, and the determination of the frequency of stars harbouring giant planets with long orbital periods.

The complete IDPS sample comprises 292 stars, covering A–M spectral types with an emphasis on massive stars (5 B-type, 107 A, 63 F, 24 G, 44 K, and 49 M).

**VLT–NACO** Of various surveys, VLT–NACO was used for a deep high-resolution survey of some 60 nearby M dwarfs, searches for giant planets within 0.1–8 arcsec (Delorme et al., 2012b; Lannier et al., 2016), and 86 stars of various spectral types between 2009–13 (Desidera et al., 2015; Chauvin et al., 2015; Reggiani et al., 2016; Vigan et al., 2017).

**Gemini–NICI** The Gemini–NICI planet finding campaign started in December 2008, included 300 targets, and achieved median contrasts of 12.5–15 mag at 0.5–1.0 arcsec (Wahhaj et al., 2011a, 2013a). Results include a close substellar companion to the young debris disk star PZ Tel (Biller et al., 2010), an L dwarf companion to the young M dwarf CD–35 2722 (Wahhaj et al., 2011b), substellar companions around the young star HD 1160 (Nielsen et al., 2012), polarimetry of the circumstellar ring around HR 4796A (Wahhaj et al., 2014; Perrin et al., 2015), and a second-epoch detection of HD 100546 b (Currie et al., 2014d).

It has provided constraints on planets around 80 stars in the young moving groups  $\beta$  Pic, TW Hya, Tuc–Hor, AB Dor, and Her–Lyr (Biller et al., 2013b), around 57 debris disk stars (Wahhaj et al., 2013b), and around 70 young nearby A and B stars including  $\beta$  Pic and Fomalhaut (Nielsen et al., 2013a). One conclusion of the non-detections by Nielsen et al. (2013a) is that  $\leq 20\%$  of  $2M_{\odot}$  stars can have giant planets  $> 4M_J$  between 59–460 au, fewer than 10% can have a planet  $> 10M_J$  between 38–650 au, and fewer than 10% of B and A stars can have an analogue to the planet HR 8799 b ( $7M_J$ , 68 au).

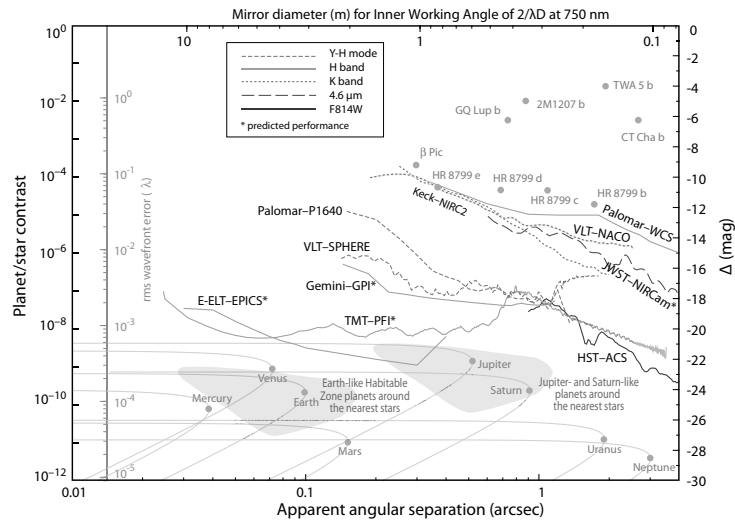


Figure 7.18: Current and projected high-contrast imaging from ground and space as a function of angular separation. The left axis shows the planet/star contrast ratio, and the corresponding required rms wavefront quality. The right axis shows the corresponding  $\Delta$  mag relative to the star. All detectivity curves are  $5\sigma$ , for 1-h integration. It includes first- (Keck-NIRC2, VLT-NACO, Palomar-WCS, HST-ACS), second- (Palomar-P3K-P1640, Gemini-GPI, VLT-SPHERE), and projected 'third-generation' (JWST-NIRCam, TMT-PFI, and E-ELT-EPICS) instruments. K-band fluxes are shown for some imaged planets, along with the solar system planets in reflected light around a Sun-like star at 10 pc. The plot merges a diversity in wavelength, and an overlap between reflected light and thermal emission regimes. Adapted from Mawet et al. (2012b, Figure 1), with permission ©SPIE.

**Subaru-SEEDS** The SEEDS survey (Strategic Exploration of Exoplanets and Disks with Subaru) was a 5-yr, 120-night, uniform and complete, high-contrast imaging planet-search programme using Subaru-HiCIAO (Janson et al., 2013b; Tamura, 2016). SEEDS consisted of two main observing modes (§7.4.5): *polarised differential imaging*, in which a Wollaston prism separates the two linear polarisation directions, the two being subtracted to construct a map of polarised intensity, and *angular differential imaging*, in which field rotation is used to distinguish point sources from quasi-static speckles (Brandt et al., 2013).

Polarised differential imaging has been used to image young circumstellar disks, including known debris disks such as HIP 79977 (Thalmann et al., 2013), and discovering large central gaps (Hashimoto et al., 2011, 2012; Mayama et al., 2012) and spiral structure in HD 169142 (Muto et al., 2012, cf. Figure 7.30). These examples of transition disks (§10.3.8) may point to unseen planets.

SEEDS included searches for substellar companions using angular differential imaging for several hundred nearby stars, discovering one cold brown dwarf, GJ 758B in commissioning (Thalmann et al., 2009; Janson et al., 2011b). Other substellar companions discovered during the main survey include GJ 504 b ( $M_p \sim 4M_J$ ,  $T \sim 510$  K), which orbits at  $\sim 43.5$  au (Kuzuhara et al., 2013; Janson et al., 2013a, see Figure 7.19);  $\kappa$  And b (Carson et al., 2013; Hinkley et al., 2013, see Figure 7.20); and other candidates and confirmations (Uyama et al., 2017a).

Other observations with Subaru-HiCIAO include a deep imaging search for planets in the Pleiades (Yamamoto et al., 2013), and high-contrast imaging of intermediate-mass gas giants with long-term radial velocity trends (Ryu et al., 2016a).

SEEDS observations, in addition to discovering new substellar companions, have placed constraints on the frequency of massive debris disks (Janson et al., 2013b), and on the population of wide-separation planets (Brandt et al., 2014a,b). SEEDS data, combined with other surveys, require that the planet population found by radial velocity surveys cannot be extrapolated beyond 30–70 au. Data are most consistent with a single substellar population, from  $5M_J$  up to the H-burning limit.

**LBT-LEECH** A 100-night high-contrast exoplanet imaging survey with the LBT, LEECH (LBTI Exozodi Exoplanet Common Hunt), started in early 2013 (Skemer et al., 2014a). Results include: further constraints on the planet architecture of the HR 8799 system (Maire et al., 2015), characterisation of the coldest directly imaged exoplanet GJ 504 b (Skemer et al., 2016), orbit and component masses of the intermediate-age late-type binary NO UMa (Schlieder et al., 2016b).

### 7.9.2 Searches with second-generation instruments

Various search programmes are being undertaken with the second-generation imaging instruments SPHERE and GPI. Results on some specific systems are detailed further in Section 7.10.

**VLT-SPHERE** First light for VLT-SPHERE (§7.6.2) was in June 2014. Early results include detection and characterisation of the substellar companion GJ 758B (Vigan et al., 2016a), the physical properties and architecture of the young systems PZ Tel and HD 1160 (Maire et al., 2016), characterisation of the HR 8799 system (Zurlo et al., 2016; Bonnefoy et al., 2016; Apai et al., 2016), morphology and photometry of the HR 4796A dust ring (Milli et al., 2017b), detection of concentric rings in the debris disk system HIP 73145 (Feldt et al., 2017); three radial gaps in the TW Hya disk (van Boekel et al., 2017); observations of the T Cha disk (Pohl et al., 2017b); discovery of a red, very dusty  $15 - 30M_J$  object in the debris disk system HD 206893B (Milli et al., 2017a; Delorme et al., 2017); and of a faint red companion of the young A2 star HIP 65426 (Chauvin et al., 2017).

**Gemini-GPI** First-light for Gemini-GPI (§7.6.2) was in November 2013 (Macintosh et al., 2014). These achieved an H-band Strehl ratio of  $\sim 0.9$ , and a  $5\sigma$  contrast of  $10^6$  at 0.75 arcsec and  $10^5$  at 0.35 arcsec.  $\beta$  Pic b, at a separation  $434 \pm 6$  mas, was detected in 60 s.

Other early results include the discovery, spectroscopy and astrometry of the young Jovian planet 51 Eri b (Macintosh et al., 2015; De Rosa et al., 2015; Rajan et al., 2017), the giant-planet-forming region of the TW Hya disk (Rapson et al., 2015), scattered-light image of the HD 131835 debris disk (Hung et al., 2015), polarimetry of the HR 4796A circumstellar ring (Perrin et al., 2015), polarised light imaging of the HD 142527 transition disk (Rodigas et al., 2014b), spectroscopy of HR 8799 planets c and d (Ingraham et al., 2014), and resolved imaging of the HD 100546 protoplanetary system, with evidence for multiple accreting planets (Currie et al., 2015).

### 7.9.3 Searches around exoplanet host stars

Especially for the first-generation imaging instruments, high-resolution observations around known exoplanet host stars often had the primary goal of further characterising the host star stellar multiplicity. For other programmes, especially the second-generation instruments, the primary goal has been planet detection. Naturally, these objectives frequently overlap.

**Surveys probing stellar multiplicity** Many speckle imaging (§7.3.2), lucky imaging (§7.3.2), adaptive optics imaging, and space imaging searches have been made around stars already known to possess orbiting planets to characterise stellar multiplicity. In addition to characterising the nature of the host star for formation studies, undetected stellar companions can bias the derived radii for transiting planets (Ciardi et al., 2015a).

Some implications of these survey results on the understanding of the occurrence of planets in multiple star systems is given in Section 10.12.4.

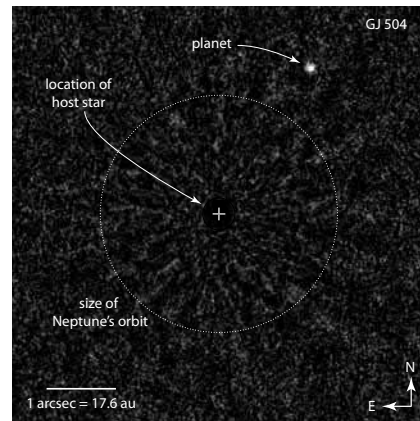


Figure 7.19: Imaging of the exoplanet GJ 504 b with Subaru-HiCIAO (2011–12) over a  $6 \times 6$  arcsec<sup>2</sup> field, showing the S/N after suppression of the flux from the central star. The planet is at a projected distance of 43.5 au. The original colour-coded image shows both the H and J band images spaced by almost one year, also revealing the planet's orbital motion. Neptune's orbit,  $a \sim 30$  au, is shown for comparison. From Kuzuhara et al. (2013, Figure 5b), by permission of IOP Publishing/AAS.

**Examples** Some representative examples of these programmes include: KPNO, CTIO and Gemini-N-DSSI speckle interferometry of Kepler and CoRoT targets (Mason et al., 2011); AEOS adaptive optics imaging (Roberts et al., 2011), VLT-NACO imaging of CoRoT candidates (Guenther et al., 2013); VLT-NACO imaging of 59 young, nearby, and dusty stars (Rameau et al., 2013a); MMT-ARIES imaging of Kepler candidates (Adams et al., 2013a; Dressing et al., 2014); Spitzer-IRAC imaging of 14 planet host stars within 15 pc (Hulsebus et al., 2014); Gemini-N-DSSI speckle observations (Kane et al., 2014a; Coker et al., 2017; Wittrock et al., 2017); CAHA-AstraLux lucky imaging of 174 Kepler objects (Lillo-Box et al., 2014a); wide-separation search using cross-matching with the VISTA-VHS and 2MASS surveys (Lodieu et al., 2014), Keck II aperture-mask interferometry (Kraus et al., 2016), and VLT-SPHERE observations of planetary systems of different orbital eccentricity (Moutou et al., 2017).

Mugrauer et al. (2014b), for example, estimated a multiplicity rate of exoplanet host stars of  $\sim 13\%$ , while Lodieu et al. (2014) found 5% for projected separations  $\geq 60 - 160$  au.

**Kepler host stars** For Kepler host stars, including candidate systems, Law et al. (2014c) found 53 companions to 715 Kepler candidates, of which 43 were new discoveries, together yielding an overall nearby-star probability for Kepler planet candidates of  $7.4 \pm 1.0\%$ . From a survey of 174 KOIs, Lillo-Box et al. (2014a) estimated that 67% were isolated, 33% have at least one visual component with  $\Delta\theta < 6$  arcsec, and 17% with  $\Delta\theta < 3$  arcsec.

Horch et al. (2014) carried out (WIYN 3.5-m and Gemini-N 8.1-m) speckle imaging for 600 Kepler KOIs, and detected 49 stellar companions within  $\sim 1$  arcsec. Assuming binary stars follow a log-normal period distribution over  $T_{\text{eff}} = 3000 - 10000$  K, they concluded that the majority of detected sub-arcsec companions are long period ( $P > 50$  yr), gravitationally bound companions, with an overall binary fraction of planet hosting stars similar to the 40–50% rate observed for field stars.

Various other imaging surveys, with similar multiplicity-characterising objectives, have been carried out: for 22 KOIs

with Earth-sized candidates by Cartier et al. (2015), for 23 GKM host stars by Gilliland et al. (2015a), for 382 KOIs (Kraus et al., 2016), for 84 blended KOIs by Atkinson et al. (2017), and for 170 KOIs hosting small planets by Hirsch et al. (2017).

Robotic laser adaptive optics imaging (Robo-AO, sensitive to  $\Delta\theta \sim 0.15 - 2.5$  arcsec and  $\Delta m \lesssim 6$  mag) is targeting every Kepler planet candidate host star, to date covering 715 targets (Law et al., 2014c), 969 targets (Baranec et al., 2016) and 1629 targets (Ziegler et al., 2017). Latest results give an overall nearby-star probability for Kepler planet candidates of  $12.6 \pm 0.9\%$  at separations 0.15–4.0 arcsec (Ziegler et al., 2017).

**Surveys targeting known planets** Other deep adaptive optics searches have a primary goal of imaging planets already discovered by other methods, and all of these are currently without success. They include:

- a Keck search around 25 stars (Luhman & Jayawardhana, 2002), and a VLT-NACO and CFHT-PUEO-KIR search around 26 stars, six with long-term radial velocity drifts (Chauvin et al., 2006);
- a VLT-NACO and MMT search around 54 stars using (CH<sub>4</sub>-band) simultaneous differential imaging (Billler et al., 2007). With H-band contrasts of 9–10 mag, survey sensitivity was  $7M_J$  at 15 au from a 70 Myr K1 star at 15 pc, and  $8M_J$  at 2 au from a 12 Myr M star at 10 pc;
- a Gemini-ALTAIR search around 85 nearby young stars using angular differential imaging (Lafrenière et al., 2007a), with sensitivity to reach  $2M_J$  at 40–200 au.

Specific coronagraphic searches include: 55 Cnc using HST-NICMOS (Schneider et al., 2001) which failed to confirm the disk reported by Trilling & Brown (1998); GJ 86 using VLT-NACO (Lagrange et al., 2006); and  $\epsilon$  Eri using VLT-NACO-SDI (Janson et al., 2007).

#### 7.9.4 Searches around binary stars

As established from other detection techniques, circum-binary planets likely constitute a significant fraction of the overall planet population. Dynamical interactions with the host binary may also launch circum-binary planets that formed or migrated inwards onto wide orbits where they are more easily imaged. Detection through imaging, especially around tight binaries, may not pose specific observational barriers, while differences in planet demographics between circum-binary and single-star hosts may bring further insights into the physics of planet formation and evolution.

Observations of young nearby tight binaries are being made with VLT-NACO, VLT-SPHERE, and LBT-LMIRCAM (Thalmann et al., 2014a; Bonavita et al., 2016). The first phase of this ‘SPOTS’ programme (Search for Planets Orbiting Two Stars) observed 27 targets with VLT-NACO (Thalmann et al., 2014a). For their total sample of 117 tight binary systems, Bonavita et al. (2016) found that just five have substellar companions, two of which (HIP 59960 b and 2M J0103–55 b) are in the planetary mass regime. This yields an upper limit of  $\lesssim 13\%$  of tight binaries hosting substellar companions

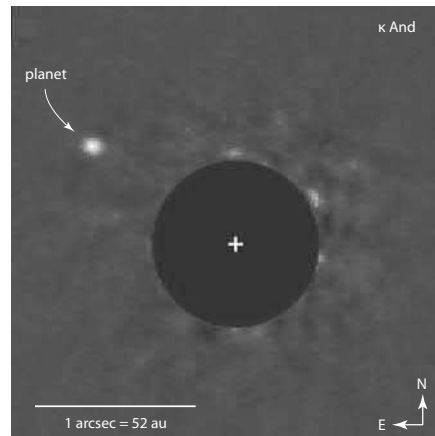


Figure 7.20:  $L'$ -band image of  $\kappa$  And b from the 2012 July observations with the Subaru AO188 system. From Carson et al. (2013, Figure 1c), by permission of IOP Publishing/AAS.

( $2 - 70M_J$ ) within 1000 au, or  $\lesssim 9\%$  for companions of planetary mass ( $2 - 15M_J$ ) within 1000 au.

This moderately low frequency of substellar companions in wide orbit is not significantly different between single stars and tight binaries, and consistent with the Kepler statistics. One implication of this result is that the very high frequency of circumbinary planets in wide orbits around post-common-envelope binaries, implied by eclipse timing (Chapter 4), cannot be only due to planets formed before the common-envelope phase (first generation planets), supporting instead a second generation planet formation (or a non-Keplerian origin of the timing variations).

#### 7.10 Discoveries

Adhering to the compilation of the NASA Exoplanet Archive, the first 5 imaging discoveries were 2M J1207 (Chauvin et al., 2005a), DH Tau (Itoh et al., 2005), GQ Lup (Neuhäuser et al., 2005), AB Pic (Chauvin et al., 2005b), and CHXR 73 (Luhman et al., 2006). Along with various others came the discoveries of planets in the well-studied systems Fomalhaut (Kalas et al., 2008), the first three planets of the 4-planet system HR 8799 (Marois et al., 2008b), and  $\beta$  Pic (Lagrange et al., 2009b).

By the end of 2017, the NASA Exoplanet Archive listed 44 exoplanet imaging discoveries (Table 7.6). A subset is shown schematically in Figure 7.21, illustrating the relevant scales of mass and separation. A concise bibliography of all systems is given in Appendix F.

**Discovery space** Inspection of Table 7.6 illustrates that objects are being discovered with a variety of instruments, both from space (HST and Spitzer), and in even larger numbers with adaptive optics on large telescopes from the ground, most notably with VLT-NACO, Keck-NIRC2, Subaru-HiCIAO, Gemini-GPI, and VLT-SPHERE.

Table 7.6: Companion objects detected by direct imaging (planet designation omitted except for multiple planets). Objects are from the NASA exoplanet archive, as of end 2017, unless indicated \*. The listing includes an incomplete compilation of brown dwarf companions (not listed in the NASA exoplanet archive, but included for comparison), objects on the border between brown dwarfs and high-mass planets ( $M_p > 13M_J$ ), planets in pronounced debris disk systems, and other probable planets (chronological within each category). Note that some of the host objects are themselves brown dwarfs. A selection is shown in Figure 7.21 to illustrate relevant scales of mass and separation. A more complete bibliography is given in Appendix F.

Object	V (mag)	ST	$M_\star$ ( $M_\odot$ )	$d_\star$ (pc)	$M_p$ ( $M_J$ )	$a''$ (arcsec)	$a$ (au)	Discovery instrument	Reference
Brown dwarfs:									
GJ 229 B*	8.1	M1V	0.6	6	20–50	7.8	45	Palomar–AOC	Nakajima et al. (1995)
GJ 758 B*	6.4	G9V	0.97	15	10–40	1.9	29	Subaru–HiCIAO	Thalmann et al. (2009)
PZ Tel B*	8.3	K0V	1.02	50	24–40	0.3	15	VLT–NACO	Mugrauer et al. (2010)
Borderline mass:									
GQ Lup	12.4	K7V	0.7	139	21	0.7	100	VLT–NACO	Neuhäuser et al. (2005)
AB Pic	9.1	K2V	0.83	47	14	5.5	248	VLT–NACO	Chauvin et al. (2005b)
HD 203030	8.4	G8V	1.0	40	24	12.2	487	Hale–PHARO	Metchev & Hillenbrand (2006)
HN Peg	6.0	G0V	–	18	16	43.0	795	Spitzer–IRAC	Luhman et al. (2007b)
Oph 11	–	M9	0.02	125	14	1.9	243	Gemini–NIRI	Close et al. (2007)
USco CTIO 108	–	M7	0.06	145	14	4.6	670	WHT–ACAM	Béjar et al. (2008)
CT Cha	13.0	K7V	–	165	17	2.7	440	VLT–NACO	Schmidt et al. (2008)
FU Tau	–	M7	0.05	140	16	5.7	800	Spitzer–IRAC	Luhman et al. (2009)
2M J2140	–	M8	0.08	25	21	–	–	Keck–NIRC2	Konopacky et al. (2010)
HIP 78530	7.2	B9V	2.5	157	23	4.7	740	Gemini–NIRI	Lafrenière et al. (2011)
GSC 0621	12.4	K7	0.9	145	16	2.2	320	Hale–PHARO	Ireland et al. (2011)
WISEP J1217	–	T8	0.03	10	22	0.8	8	Keck–NIRC2	Liu et al. (2012)
$\kappa$ And	4.1	B9IV	2.6	52	14	1.1	55	Subaru–HiCIAO	Carson et al. (2013)
2M J0122	14.2	M3V	0.4	36	25	1.4	52	Keck–NIRC2	Bowler et al. (2013)
ROXs 12	15.6	M0	0.87	120	16	1.8	210	Keck–NIRC2	Kraus et al. (2014)
2M J0219	–	M6	0.11	39	14	4.0	156	CTIO–SIMON	Artigau et al. (2015)
HR 2562	6.1	F5V	1.3	34	30	0.6	20	Gemini–GPI	Konopacky et al. (2016b)
Debris disks:									
Fomalhaut	1.2	A3V	2.1	8	3	15.0	119	HST–ACS	Kalas et al. (2008)
HR 8799 b	6.0	F0+V	1.5	39	7	1.7	68	Keck/Gemini	Marois et al. (2008b)
" c	"	"	"	"	10	1.0	38	"	"
" d	"	"	"	"	10	0.6	24	"	"
" e	"	"	"	"	~10	0.4	15	Keck–NIRC2	Marois et al. (2010)
$\beta$ Pic	3.9	A5V	1.8	19	8	0.4	12	VLT–NACO	Lagrange et al. (2009b)
Other:									
2M J1207	20.2	M8	0.03	70	4	0.8	46	VLT–NACO	Chauvin et al. (2005a)
DH Tau	13.1	M1V	0.33	140	11	2.4	330	Subaru–HiCIAO	Itoh et al. (2005)
CHXR 73	–	M3	–	161	12	1.3	210	HST–ACS	Luhman et al. (2006)
1RXS J1609	–	K7V	0.85	150	8	2.2	330	Gemini–NIRI	Lafrenière et al. (2008)
2M J0441	–	M8	0.02	140	7	0.1	15	HST/Gemini	Todorov et al. (2010b)
Ross 458	9.7	M0	–	140	6	8.3	1168	Magellan–FIRE	Burgasser et al. (2010b)
SR 12AB	13.3	–	–	–	13	–	–	IRSF–SIRIUS	Kuzuhara et al. (2011)
WD 0806–661	–	–	0.62	19	7	131	2500	Spitzer–IRAC	Luhman et al. (2011)
CFBD J1458	–	–	0.02	23	10	0.1	2.6	Keck–NIRC2	Liu et al. (2011b)
GJ 504	5.2	G0V	1.22	18	4	2.4	43	Subaru–HiCIAO	Kuzuhara et al. (2013)
HD 95086	7.4	A8III	1.6	92	5	0.6	56	VLT–NACO	Rameau et al. (2013c)
GU Psc	13.6	M3	0.33	48	11	41.7	2000	Gemini–GMOS	Naud et al. (2014)
HD 106906	7.8	F5V	1.5	92	11	7.1	650	Magellan–Clío2	Bailey et al. (2014b)
ROXs 42B	–	M0	1.0	135	9	1.2	157	Various	Currie et al. (2014c)
HD 100546	6.7	B9V	2.4	97	–	0.6	53	VLT–NACO	Quanz et al. (2015a)
LkCa 15 b	–	–	–	–	–	–	15	LBT–LMIRCam	Sallum et al. (2015)
" c	–	–	–	–	–	–	19	LBT–LMIRCam	Sallum et al. (2015)
51 Eri	5.2	F0IV	1.75	29	2	0.5	13	Gemini–GPI	Macintosh et al. (2015)
VHS J1256	17.8	M7	0.07	13	11	7.9	102	VISTA–VIRCAM	Gauza et al. (2015)
2M J2236	12.5	K7V	0.6	74	12	3.1	230	Keck–NIRC2	Bowler et al. (2017b)
HIP 65426	7.0	A2V	2.0	111	9	0.8	92	VLT–SPHERE	Chauvin et al. (2017)

Discoveries include companions to bright stars accessible to adaptive optics (such as  $\beta$  Pic, Fomalhaut,  $\kappa$  And, and others), and to low-mass M dwarf primaries observed in the infrared, such as the 2MASS primaries observed with Keck–NIRC2. Companion masses range from the very massive 20–30 $M_J$  objects, down to the 1–2 $M_J$  objects being discovered with Gemini–GPI (e.g. 51 Eri at 2 $M_J$ ), Subaru–HiCIAO (e.g. GJ 504 b at 4 $M_J$ ), and VLT–SPHERE (e.g. HD 131399A b at 4 $M_J$ ), although the latter (Wagner et al., 2016) has been suggested to be a background star (Nielsen et al., 2017). Some 30% lie at angular separations  $< 1$  arcsec from their host star.

Most imaging discoveries are in orbits with very large semi-major axes ( $a \gg 10$  au), although a few are in the range 10–20 au, such as 51 Eri,  $\beta$  Pic, and HR 2562. More than 20 have  $a > 100$  au. These large semi-major axes can be compared with the largest separation probed by any of the other detection exoplanet techniques: the  $a \sim 20$  au of the radial velocity discovery HIP 70849 b. These very wide orbits represent planetary architectures that cannot be probed by other detection techniques, and also provide a particular challenge to theories of planetary formation and evolution.

Two multi-planet systems are known: the 4-planet system HR 8799, and the 2-planet system LkCa 15.

The following sections provide an overview of the discoveries, loosely divided into nearby stars, systems with particularly pronounced debris disks, and the discovery of resolved disk structures suggestive of the presence of unseen planets. Results of programmes targeting star-forming regions, and the low-mass tail of ‘free-floating planets’, are treated in Chapter 9. Searches around white dwarfs are treated in Section 8.9.2.

**Classification as planets or brown dwarfs** For this work, imaging discoveries are simply taken to be those included in the NASA Exoplanet Archive. This includes, for example, objects with masses above the nominal brown dwarf mass limit of  $\sim 13M_J$ . Having formed, presumably, by disk accretion, they are taken to satisfy the wider definition of a planet considered in Chapter 1.

Differences in the candidates listed in (for example) the NASA Exoplanet Archive and the Exoplanet Encyclopaedia result from at least two considerations.

The first is due to the uncertain boundary between objects that are definitively brown dwarfs on the one hand, or most probably of planetary mass on the other. Estimated companion masses are dependent on evolutionary models, in part due to difficulties of precise age determination (Figure 7.22), and objects such as AB Pic b (Chauvin et al., 2005b) and IM Lup (Mawet et al., 2012a) are correspondingly difficult to classify.

Similar uncertainty surrounds the formation mechanism of some of the low-mass objects, particularly those in wide orbits around very low-mass stars and brown dwarfs. Whether the companion has formed by one-step gravitational collapse (out of the same gas cloud as the host star), or by a two-step process involving core accretion, may prove to be an important criterion for accepting a low-mass object as a planet.

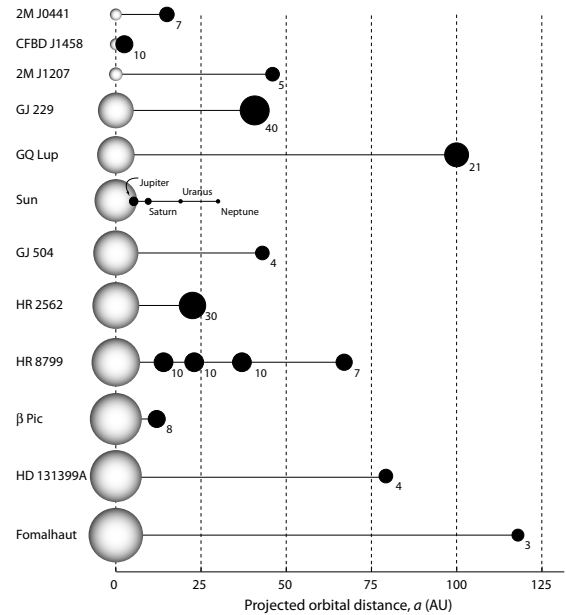


Figure 7.21: Schematic of  $M_\star$ ,  $M_p$ ,  $a$  for some of the imaged systems in Table 7.6, with the Sun and outer planets for comparison, and ordered by  $M_\star$ . The host star has size proportional to  $R_\star \propto \sqrt[3]{M_\star}$ . Companion masses are indicated in units of  $M_J$ , with  $R_p \propto \sqrt[3]{M_p}$ , and (projected) orbital distance in au.

As one example, the companion to the white dwarf WD 0806–661 (GJ 3483) was already considered in the discovery paper to be either a brown dwarf that formed like a binary star via Jeans-mass fragmentation, or a giant planet born within a disk and dynamically scattered to a larger orbit (Luhman et al., 2011), while the former has been considered to be the most likely formation mechanism by Rodriguez et al. (2011).

### 7.10.1 Planets around nearby stars

Of the reported low-mass companions (Table 7.6), one example, 2M J1207 b, is shown in Figure 7.23, although the primary is considered as a brown dwarf rather than a star. The companion, of mass 5–8 $M_J$ , was discovered using VLT–NACO (Chauvin et al., 2005a), and confirmed using HST–NICMOS (Song et al., 2006). The nature of 2M J1207 b continues to be debated (e.g. Mohanty et al., 2007; Mamajek & Meyer, 2007; Skemer et al., 2011).

**Young systems** Young, directly imaged exoplanets provide important tests of planet-formation models. As an example, LkCa 15 is a young (2 Myr) solar analogue. Kraus & Ireland (2012) reported the direct-imaging discovery of a likely (proto)planet, located inside a known gap in the protoplanetary disk. This confirms that (at least some) transition disks host newly-forming planets, with the observed properties providing insight into gas giant formation. Other examples of transition disk structures are given in Section 10.3.8.

An open question in core accretion models of giant planet formation is the initial entropy of the accreting

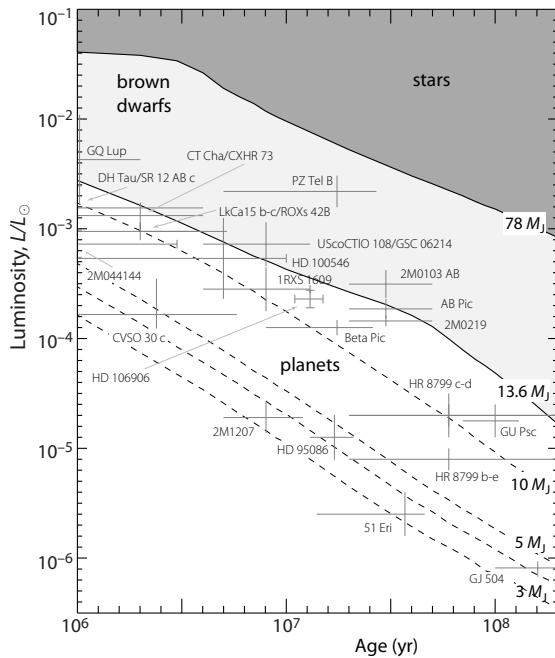


Figure 7.22: Luminosity versus time as a function of mass, with theoretical evolutionary tracks from Baraffe et al. (2015), showing companion objects detected by direct imaging. The deuterium burning limit,  $\sim 13.6M_J$ , separates planets from brown dwarfs, while the boundary between stars and brown dwarfs is set by stable H burning. Estimated companion masses depend on the assumed age of the host star. From Schmidt et al. (2016, Figure 9), reproduced with permission © ESO.

gas. Specifically, young, relatively massive planets calculated according to the ‘cold start’ model are considerably fainter than those, at the same age, calculated with a ‘hot start’. Multi-colour photometry of imaged planets is starting to provide insights into these processes. Further details are given in Section 10.5.1, along with application to 2M 1207, HR 8799,  $\beta$  Pic, and 51 Eri.

**Statistical results** Of the 292 stars comprising the International Deep Planet Survey (IDPS), Galicher et al. (2016) reported the detection of 59 visual multiple systems including 16 new binary stars and 2 new triple stellar systems, as well as 2279 point-like sources.

They used Monte Carlo simulations and Bayesian analysis to determine that, on the assumption of uniform distributions of  $M_p$  and  $a$ ,  $1.05^{+2.80}_{-0.70}\%$  of stars harbour at least one giant planet between  $0.5\text{--}14M_J$  and between  $20\text{--}300$  au. On the assumption of power law distributions, as measured for close-in planets, the derived frequency is  $2.30^{+5.95}_{-1.55}\%$ . They also find no evidence that the derived frequency depends on  $M_\star$ , whereas it does for close-in planets.

In a statistical meta-analysis of deep imaging surveys in the literature, Bowler (2016) summarises the status as follows: based on observations of 384 unique and

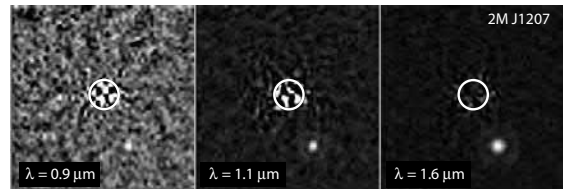


Figure 7.23: HST-NICMOS near-infrared imaging of 2M J1207 b. The star, centred in the  $0.2$  arcsec radius circle, is subtracted using a second image acquired at a different orientation. The companion lies at  $0.77$  arcsec. From Song et al. (2006, Figure 1), by permission of IOP Publishing/AAS.

single young ( $5\text{--}300$  Myr) stars spanning stellar masses between  $0.1\text{--}3.0M_\odot$ , the overall occurrence rate of  $5\text{--}13M_J$  companions at orbital distances of  $30\text{--}300$  au is  $0.6^{+0.7}_{-0.5}\%$  assuming hot-start evolutionary models. The most massive giant planets regularly accessible to direct imaging are about as rare as hot Jupiters are around Sun-like stars. Dividing this sample into individual stellar mass bins does not reveal any statistically significant trend in planet frequency with host mass: giant planets are found around  $2.8^{+3.7}_{-2.3}\%$  of BA stars,  $< 4.1\%$  of FGK stars, and  $< 3.9\%$  of M dwarfs.

Slightly different conclusions were drawn in an earlier analysis by Crepp & Johnson (2011), who made an assessment focusing on the dependence on star mass, accounting for the statistical properties of stars in the solar neighbourhood, correlations between star and planet properties, observational effects, and selection criteria. Selecting targets based on their youth and visual brightness, they found that strong correlations between star mass and planet properties are required to reproduce high-contrast imaging results for the more massive stars (i.e., HR 8799,  $\beta$  Pic), with a simple extrapolation of the Doppler planet gas giant population to semi-major axes accessible to high-contrast instruments providing very good agreement between simulations and observations.

In addition to being intrinsically young and sufficiently bright to serve as their own beacon for adaptive optics correction, A-stars have a high planet occurrence rate and propensity to form massive planets in wide orbits. In the case of young stellar clusters, where targets are approximately the same age and situated at roughly the same distance, the more common K and M stars can dominate the number of detections. Their simulations suggest that the companions found orbiting late-type stars (AB Pic, 1RXS1609, GSC 06214, etc.) are consistent with a formation channel *distinct* from that of radial velocity planets, therefore explaining why planets have thus far been imaged preferentially around A-stars and K and M-stars, but no spectral types in between.

### 7.10.2 Planets within debris disks

In 2008, imaging observations identified planets orbiting two stars surrounded by dusty debris disks (§10.6). Both stars, Fomalhaut (A3V,  $d = 7.7$  pc) and HR 8799 (A5V,  $d = 39.4$  pc), are younger, brighter, and more massive than the Sun. Subsequent imaging observations detected a planet orbiting  $\beta$  Pic.

Since masses of self-luminous planets detected by



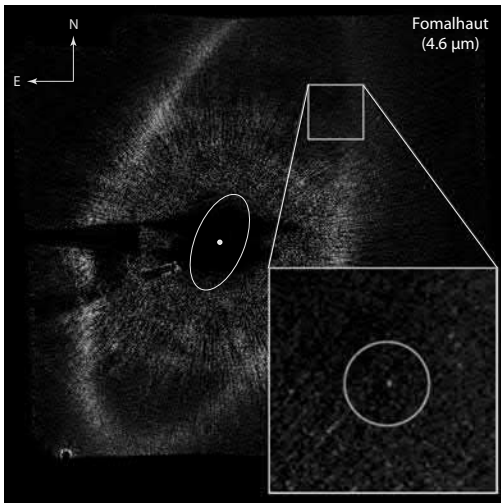


Figure 7.24: HST-ACS  $0.6\ \mu\text{m}$  coronagraphic image of Fomalhaut showing object b (inset)  $12.7\ \text{arcsec}$  ( $\sim 115\ \text{au}$ ) from the star, and just within the dust belt's inner boundary. The central circle marks star/occulting spot. The central ellipse has  $s = 30\ \text{au}$  ( $3.9\ \text{arcsec}$ ), corresponding to the orbit of Neptune. Originally published as Kalas et al. (2008, Figure 1), this version is courtesy of Paul Kalas, UC Berkeley/NASA/ESA.

imaging are typically inferred from their brightness, and since they fade as they radiate heat from their formation, mass estimates are sensitive to their assumed ages.

**Fomalhaut** The nearby (7.7 pc) star Fomalhaut is surrounded by a belt of cold dust. Its resolved structure observed with HST-ACS coronagraphy (specifically, a 15 au offset between the star and geometric centre of the belt, and a sharp truncation of its inner edge) was inferred to be consistent with gravitational clearing by an orbiting planet (Stapelfeldt et al., 2004; Kalas et al., 2005). The eccentricity and sharpness of the disk's inner edge led Quillen (2006a) to propose the existence of a planet just interior to it, with a mass between that of Neptune and Saturn, and with  $a \sim 119\ \text{au}$  and  $e \sim 0.1$ .

**Imaging results** Keck II observations in 2005, and further HST-ACS coronagraphy in 2006, led to the detection of the planet, Fomalhaut b, and showed a common proper motion with the central star, but with an offset of  $0.18 \pm 0.02\ \text{arcsec}$  over 1.7 yr corresponding to a  $0.82 \pm 0.10\ \text{au yr}^{-1}$  projected motion relative to the host star (Kalas et al., 2008, Figure 7.24). Observations are consistent with counter-clockwise orbital motion, a projected distance of 119 au, and an orbital period  $\sim 870\ \text{yr}$ .

Although the planet mass is not determined directly, dynamical models of the interaction between the planet and the disk imply  $M_p \lesssim 3M_J$ ; a higher mass would lead to gravitational disruption of the disk. Atmospheric models indicate that Fomalhaut b is a cooling Jovian-mass planet with an age of 100–300 Myr. Although faint, it is still  $\sim 100$  times brighter than reflected light from a Jupiter-like planet at that orbital radius. Subsequent observations (see Appendix F) have continued to probe the disk structure and planet characteristics.

Debate over the planetary interpretation has, however,

continued. While independent analyses of the optical HST data have confirmed the planet detection (Currie et al., 2012a; Galicher et al., 2013), searches in the infrared have not detected it (Kalas et al., 2008; Marengo et al., 2009; Janson et al., 2012b), and eccentricity of the disk structure remains unexplained (Tamayo, 2014). An alternative hypothesis is that optical images are detecting starlight scattered by a vast dust cloud, perhaps generated by recent collisional processes (Kenyon et al., 2014; Lawler et al., 2015; Kenyon & Bromley, 2015a; Tamayo, 2014), or that the object is an unrelated background neutron star (Neuhäuser et al., 2015).

**HR 8799** High-contrast observations with Keck and Gemini initially revealed three planets orbiting HR 8799, with projected separations 24, 38, and 68 au, resembling a scaled-up version of the outer solar system (Marois et al., 2008b, Figure 7.25a). Multi-epoch data show counter-clockwise orbital motion for all three planets.

**Subsequent observations** Early theoretical evolutionary models, luminosities (in J, H, and Ks), and the estimated age of the system, 30–160 Myr, initially implied companion masses 5– $13M_J$ . However, derived masses are sensitively dependent on the estimated age of the central star, being determined from the theoretical age–luminosity relation derived from brown dwarf/giant planet evolutionary tracks (Figure 7.22). Asteroseismology, with its own uncertainties due to the unknown orientation of the rotation axis, has suggested a host star age closer to 1 Gyr, and consequently companions of brown dwarf rather than planetary mass (Moya et al., 2010a; Wright et al., 2011a).

Numerous related observations have since been made (Appendix F), including the ‘precovery’ (pre-discovery recovery) of HR 8799 b in HST-NICMOS images from 1998 (Lafrenière et al., 2009). All three objects were detected with a high-performance 1.5-m sub-aperture of the Hale 5-m telescope with an optical vortex coronagraph (Serabyn et al., 2010). A fourth planet, HR 8799 e, was detected with Keck (Marois et al., 2010, Figure 7.25b), and subsequently confirmed with LBT (Skemer et al., 2012; Esposito et al., 2013).

Early dynamical modeling suggested that planets b–d may be in a Laplace configuration 1d:2c:4b (Reidemeister et al., 2009; Goździewski & Migaszewski, 2009; Fabrycky & Murray-Clay, 2010; Marshall et al., 2010; Sommer et al., 2011a).

Goździewski & Migaszewski (2014) assessed the system's dynamical stability by an optimisation of the astrometric data and a heuristic model of planet migration (Moore & Quillen, 2013), a method they referred to as the Migration Constrained Optimisation Algorithm. They showed that planets b–d are plausibly in a double Laplace resonance, with (possible) periods in the ratio 1e:2d:4c:8b (Figure 7.27a). A fifth hypothetical innermost planet f, at 9.7 au or 7.5 au, could extend this to a triple Laplace resonance, 1f:2e:4d:8c:16b or 1f:3e:6d:12c:24b.

Other results include spatially-resolved spectroscopy of HR 8799 c using VLT-NACO at  $4\ \mu\text{m}$  (Janson et al., 2010), spectroscopy of planets c and d with GPI (Ingraham et al., 2014, Figure 7.27b), thermal infrared imaging and constraints on a fifth planet (Currie et al., 2014b), and other insights from VLT-SPHIRE first-light imaging including time-resolved photometry (Zurlo et al., 2016; Bonnefoy et al., 2016; Apai et al., 2016).

**$\beta$  Pic**  $\beta$  Pic was the third prominent debris disk system in which a probable planet has been detected. Already, VLT-NACO observations revealed a  $M \sim 8M_J$  object at  $\sim 8\ \text{au}$  (Lagrange et al., 2009b, see Figure 10.24).

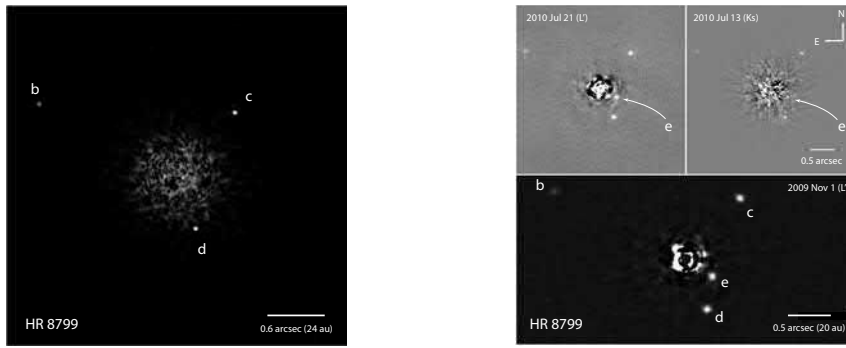


Figure 7.25: Left: combined J-, H-, and Ks-band image of HR 8799 from Keck in 2008 July (H) and September (J and Ks). Light from the host star has been removed by angular differential imaging, and left unmasked to show the speckle noise. The inner part of the H-band image has been rotated by  $1^\circ$  to compensate for the orbital motion of planet d. Originally published as Marois et al. (2008b, Figure 1), this version is courtesy: NRC–HAA, C. Marois & Keck Observatory. Right: Keck II images of HR 8799 obtained by angular differential imaging in L' and Ks (2010 July), with an L-band image using a 400 mas diameter coronagraphic focal plane mask (2009 Nov 1, bottom). Planets b, c and d are at projected separations of 68, 38 and 24 au from the central star, consistent with circular orbits at  $i < 40^\circ$ . From Marois et al. (2010, Figure 1), by permission from Nature/Springer/Macmillan Ltd, ©2010.

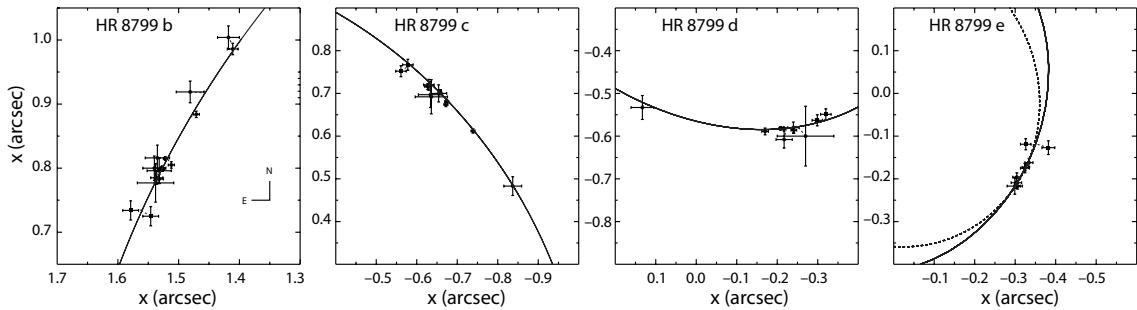


Figure 7.26: Relative astrometry of the four planets in HR 8799. Solid curves are the orbit solutions for non-coplanar circular orbits. Dashed lines connect the predicted and observed positions. For HR 8799 e, the dotted line shows the orbit solution for the 5:2 mean motion resonance with planet d. From Esposito et al. (2013, Figure 9), reproduced with permission © ESO.

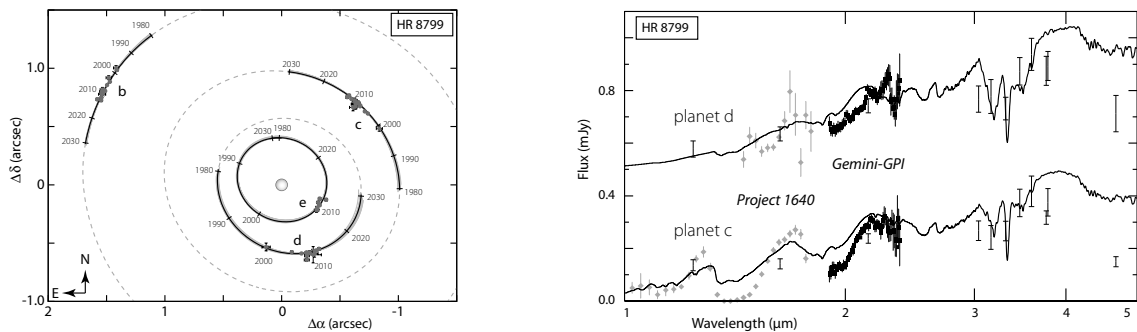


Figure 7.27: Left: relative astrometric positions of the four HR 8799 planets, based on all available observations in the literature (grey circles), orbital arcs for the best-fit model (black curves), and stable solutions within the  $3\sigma$  confidence level of the best-fit model (grey curves). The best-fitting, stable and unique orbits consistent with all astrometric data corresponds to an exact first-order mean motion resonance, the double Laplace resonance  $1e:2d:4c:8b$ . From Goździewski & Migaszewski (2014, Figure 4), © Oxford University Press. Right: spectra of HR 8799 planets c and d with Gemini–GPI (with planet d shifted up by 0.5 mJy for clarity). GPI spectral data are shown as black squares, Project 1640 spectra (Oppenheimer et al., 2013) as grey diamonds, and photometric data compiled by Skemer et al. (2014b) as thin error bars alone. Solid curves are cloudy models with  $T_{\text{eff}} = 1100$  K,  $g = 10^2$  m s $^{-1}$ , and solar abundance. The model for planet c has a cloud sedimentation parameter  $f_{\text{sed}} = 0.25$  and a partial cloud cover with 5% holes. The model for planet d has  $f_{\text{sed}} = 0.5$  and no holes. Model fluxes are scaled with radius from evolutionary models (Saumon & Marley, 2008). From Ingraham et al. (2014, Figure 2), by permission of IOP Publishing/AAS.

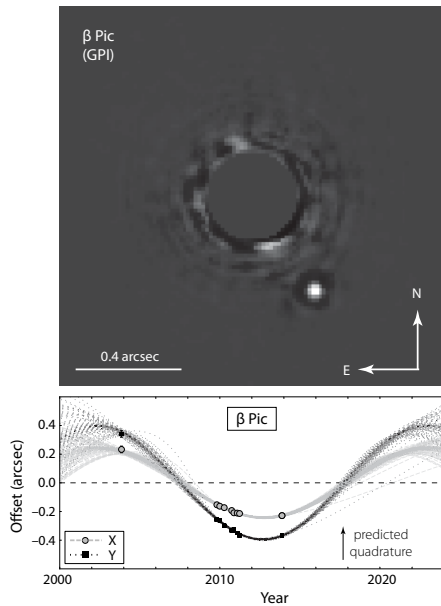


Figure 7.28: Top: 30-min GPI broad-band ( $1.5\text{--}1.8\ \mu\text{m}$ ) image of  $\beta$  Pic, following PSF subtraction using angular and spectral differential techniques. The planet,  $\beta$  Pic b, is detected at a signal-to-noise of  $\sim 100$ . Bottom: projected separation of  $\beta$  Pic b. Data prior to GPI in late 2013 are from Chauvin et al. (2012b). The GPI measurement shows that  $\beta$  Pic b has passed quadrature, with conjunction predicted in Sep–Dec 2017. X and Y trajectories show 100 orbit solutions determined from Monte Carlo analyses. From Macintosh et al. (2014, Figures 2 and 4), with permission ©(2014) National Academy of Sciences.

Subsequent imaging (see also Appendix F) includes VLT–NACO (Quanz et al., 2010b; Lagrange et al., 2010a; Bonnefoy et al., 2011; Absil et al., 2013b), confirmation with Gemini–NICI (Boccaletti et al., 2013; Nielsen et al., 2014), Gemini–GPI (Bonnefoy et al., 2014b; Macintosh et al., 2014), and Magellan–Clio (Morzinski et al., 2015). A Gemini–GPI image is shown in Figure 7.28, although orbits have since been updated (Millar-Blanchaer et al., 2015; Wang et al., 2016b).

Lecavelier des Etangs & Vidal-Madjar (2009) suggested the association of the planet with the rapid photometric variations observed on 1981 November 10, that were already attributed to the transit of a giant comet (Lamers et al., 1997) or a planet at several au (Lecavelier des Etangs et al., 1995). Evidence for an inferred exocomet population is discussed in Section 6.23.

**Others** Other disks have been imaged to characterise structure and identify embedded planets. Gemini–GPI polarimetric imaging of the HR 4796A disk is shown in Figure 7.29. Others include: HD 100546 (Quanz et al., 2013a; Avenhaus et al., 2014a; Pineda et al., 2014), HD 169142 (Honda et al., 2012; Quanz et al., 2013b; Osorio et al., 2014; Reggiani et al., 2014; Ligi et al., 2018), and HD 206893B (Milli et al., 2017a; Delorme et al., 2017).

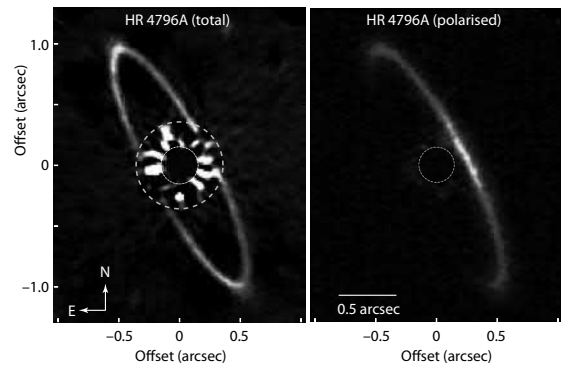


Figure 7.29: GPI polarimetry of HR 4796A (2014 March 25). Left: PSF-subtracted total intensity image resulting from angular differential imaging (ADI) reduced using the GPI-pipeline KLIP algorithm. The inner dark circle indicates the coronagraph occulting mask, 0.3 arcsec in diameter. Right: polarised intensity, showing that the disk is strongly polarised on the west side. The very uniform and dark background results from efficient stellar PSF suppression (the central dashed circle indicates the coronagraphic occulting spot size). From Perrin et al. (2015, Figures 7c and 11a), by permission of IOP Publishing/AAS.

**Orbital motion** As evident from a number of the imaging observations, and for example in Figures 7.26–7.27, multi-epoch observations are now revealing planetary orbital motion. These are visualised in video sequences for HR 8799,  $\beta$  Pic, Fomalhaut, and 51 Eri.<sup>1</sup>

### 7.10.3 Disks with spiral arms

Several resolved young stellar disks are observed to have a spiral structure, amongst them MWC 758 (Isella et al., 2010; Grady et al., 2013; Benisty et al., 2015), HD 135344B/SAO 206462 (Muto et al., 2012; Garufi et al., 2013; Pérez et al., 2014), Oph IRS48 (Follette et al., 2015), and HD 100453 (Wagner et al., 2015a). Two spiral arms are the most common (e.g., HD 135344B/SAO 206462, HD 100453, and MWC 758; Figure 7.30a–c), although single arms are also found, as in Oph IRS48 (Follette et al., 2015) and V1247 Ori (Kraus et al., 2013).

One interpretation is that the spiral structure arises from gravitational instabilities induced by an unseen planet with  $M_p/M_\star \sim 10^{-2}$  (Pohl et al., 2015), a hypothesis directly supported by recent observations of HD 100453 (Wagner et al., 2018). Density wave theory can predict the planet’s location and mass, and the temporal evolution of the spiral arms, which could be observable over 10–20 yr (Muto et al., 2012).

<sup>1</sup> Videos showing the orbital motion of the four HR 8799 planets from 7 Keck observations over 7 yr,  $\beta$  Pic b from 9 Gemini–GPI observations over 2 yr, and Fomalhaut b from 5 HST observations over 7 yr are available online at [jasonwang.space/orbits.html](http://jasonwang.space/orbits.html). Others include a longer (2003–16, unsmoothed) VLT–NACO/SPHERE video of  $\beta$  Pic b, and a Gemini–GPI short arc-length sequence of 51 Eri b.

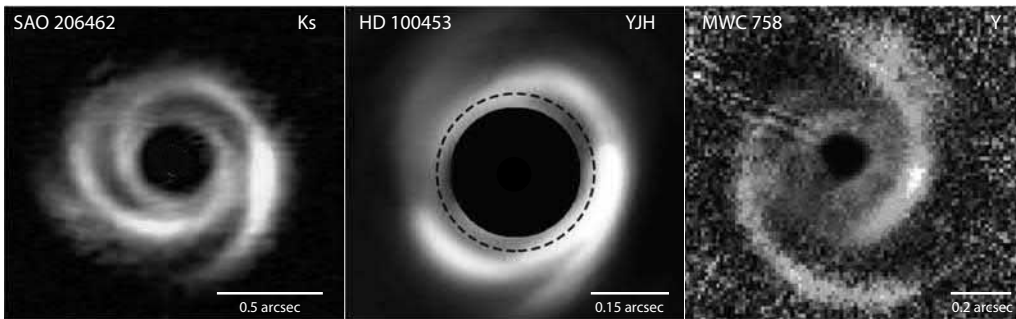


Figure 7.30: Spiral disks around young stars resolved in high-contrast imagery: HD 135344B/SAO 206462 (Garufi et al., 2013, Figure 1), HD 100453 (Wagner et al., 2015a, Figure 4), and MWC 758 (Benisty et al., 2015, Figure 1). Black central masks are regions obscured by the coronagraph. Reproduced by permission of IOP Publishing/AAS and © ESO, respectively.

Subaru-CIAO imaging of SR 24 in the Ophiuchus star-forming region resolved both circumprimary and circumsecondary disks, and revealed both a bridge of emission between the two, and a long spiral arm extending from the former (Mayama et al., 2010).

Imaging combined with spectroscopy is leading to many physical insights into these disk structures, and the inferred distributions of gaps, dust grains, and sizes. In models of the transition disk system HD 135344B/SAO 206462, for example, Garufi et al. (2013) infer the presence of a planet which is responsible for carving out the large region of highly-depleted dust (observed at mm wavelengths), surrounded by a dust rim that can act as a filter, holding back large dust grains but allowing small particles to move inward.

## 7.11 Miscellaneous signatures

### 7.11.1 Planetary and protoplanet collisions

Stern (1994) considered the detectability of giant impacts during late stages of planet formation. Massive colliding and accreting pairs, with  $M \sim 0.1 M_{\oplus}$ , would deposit sufficient energy to turn their surfaces molten and temporarily render them much more luminous in the infrared, with ocean vaporisation or energy radiation to space dominating according to mass. This occurs even for low-velocity approaches (i.e. for co-planar, circular orbits at 1 au), the gravitational attraction leading to impact velocities of around  $10 \text{ km s}^{-1}$ . A luminous 1500–2500 K photosphere persisting for  $10^3 \text{ yr}$  could be created for a terrestrial-mass planet (giant planet impacts would be more luminous but shorter lived) leading to an estimate of 1/250 young stars affected.

Planet–planet collisions are also possible in quasi-mature planetary systems as a consequence of planet–planet perturbations. Zhang & Sigurdsson (2003) investigated the expected collision rate, and the typical associated electromagnetic signals. An Earth–Jupiter collision would give rise to a prompt extreme ultra-

violet/soft X-ray flash lasting for hours, and a bright infrared afterglow lasting for thousands of years. Signals would be above the X-ray detectability limits of Chandra and XMM, and possibly above the photometric detection capabilities of Gaia. Other estimates of detection prospects have been given (Kenyon & Bromley, 2005; Anic et al., 2007; Miller-Ricci et al., 2009).

*2M J1207 b*: The imaged system 2M J1207 b (§7.10.1) has been proposed as an example of such a collisional process (Mohanty et al., 2007). Its apparently sub-luminous nature has been explained as a hot protoplanet collision afterglow, with specific predictions which follow for its surface gravity (Mamajek & Meyer, 2007).

*2M J0809–48 (ID8)*: The infrared disk emission of the young solar analogue ID8 varies on a 1-yr time scale, and has been attributed to a violent collision yielding a silica-rich vapour plume (Meng et al., 2012, 2014). Meng et al. (2014) monitored four other ‘extreme debris disks’ (with disk fractional luminosity  $> 10^{-2}$ ) around solar-like stars with ages 10–120 Myr, detecting infrared variations consistent with collisional events.

### 7.11.2 Accretion onto the central star

One terminal stage of an inspiraling planet may be its accretion onto the star, in the form a planet–star merger.

**Final stellar evolutionary stages** Modeling has been carried out for stars in their final evolutionary stages of outer envelope expansion, notably for asymptotic giant branch stars (Siess & Livio, 1999a) and for solar-mass stars on the red giant branch (Siess & Livio, 1999b).

In the latter case, observational signatures that accompany the engulfing of the planet include ejection of a shell and a subsequent phase of infrared emission, increase in the  ${}^7\text{Li}$  surface abundance, spin-up of the star because of the deposition of orbital angular momentum, and the possible generation of magnetic fields and the related X-ray activity caused by the development of shears at the base of the convective envelope.

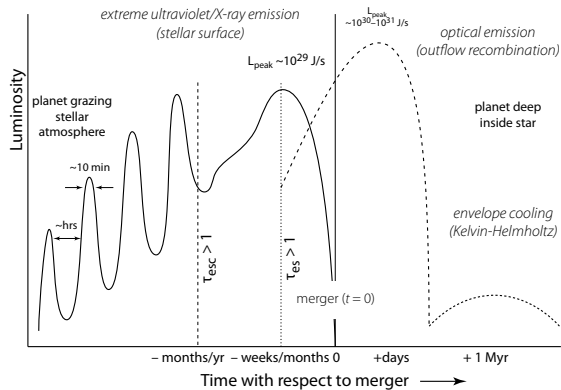


Figure 7.31: Schematic light curve of a planet–star merger. At early times, EUV/X-ray emission (solid curve) originates from the hot layer behind the planet as it grazes the stellar atmosphere. Initially the signal is periodic on the orbit time scale of  $\sim$  hours, with atmospheric heating increasing as the planet sinks deeper. Electron scattering suppresses X-ray periodicity months to a year prior to merger ( $\tau_{\text{esc}} \gtrsim 1$ , dashed vertical line). Scattered (roughly isotropic) high-energy radiation escapes for weeks/month prior to merger, before being entirely suppressed by inelastic electron scattering and free-free absorption weeks/month prior to merger ( $\tau_{\text{abs}} \gtrsim 1$ , dotted vertical line). At late times, thermal optical emission from the photospheric wind (dashed curve) becomes increasingly bright, largely through H recombination. The final dynamical stages result in the ejection of a shell of ionised material, from which thermal emission powers an optical transient lasting  $\sim$  day(s). Finally, gravitational energy released by the planet deep inside the star is radiated on the much longer Kelvin–Helmholtz cooling time scale of the stellar envelope  $\sim 10^6$  yr (dotted curve). From Metzger et al. (2012a, Figure 8), © Oxford University Press.

**Tidal mergers of hot Jupiters** The angular momentum of many, perhaps most, hot Jupiters is sufficiently low that no state of tidal equilibrium exists, and the system is ‘Darwin unstable’ (§10.11.4), suggesting that the ‘end state’ of tidal dissipation is a merger between planet and host star (e.g. Jackson et al., 2008b). Depending on the quality factor of tidal dissipation within the star  $Q'_* \sim 10^6$  (§10.11.3), the semi-major axes of several hot Jupiters are sufficiently small that a merger will indeed occur on relatively short time scales  $\leq 10 - 100$  Myr (e.g. Li et al., 2010b). The lack of old planetary systems with very short orbital periods hints that mergers indeed result from tidal orbital decay (Jackson et al., 2009).

Since  $\sim 1\%$  of stars host hot Jupiters (e.g. Mayor & Queloz, 2012), and since the Galactic star-formation rate is  $\sim 1 - 10 \text{ yr}^{-1}$  (Naab & Ostriker, 2006), then the Galactic rate of planet–star mergers might be expected to be  $\leq 0.1 \text{ yr}^{-1}$ . But the actual merger rate with main sequence stars can be significantly higher,  $\sim 1 \text{ yr}^{-1}$ , depending on  $Q'_*$ , and the rate at which they are replenished by migration from the outer stellar system (Socrates et al., 2012).

Metzger et al. (2012a) evaluated the prompt observational signatures of the merger between a massive close-

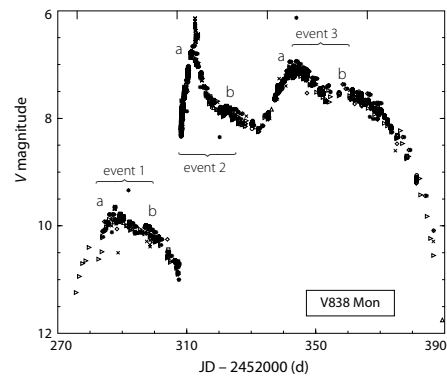


Figure 7.32: The light curve of V838 Mon over 120 d in 2002, showing three similar ‘double outburst’ events, each comprising major and minor peaks (a/b). Bursts have been attributed to a planet being slowed in three separate density-driven stages, and finally being engulfed in the envelope of a massive B star. From Retter et al. (2006, Figure 1), © Oxford University Press.

in hot Jupiter and its host star, events with an estimated Galactic rate of  $\sim 0.1 - 1 \text{ yr}^{-1}$ . Depending on the mean density ratio  $\bar{\rho}_p/\bar{\rho}_*$ , a planet–star merger results in three possible outcomes. For  $\bar{\rho}_p/\bar{\rho}_* \geq 5$ , the planet directly plunges below the stellar atmosphere before being disrupted by tidal forces (Figure 7.31).

The dissipation of orbital energy creates a hot wake behind the planet, producing an EUV/soft X-ray transient that increases in brightness and temperature as the planet sinks below the stellar surface. The peak luminosity  $L_{\text{EUV/X}} \leq 10^{29} \text{ J s}^{-1}$  is achieved weeks to months prior to merger, after which the stellar surface is enshrouded by a merger-driven outflow. The final inspiral stages are accompanied by an optical transient, powered by H recombination in the outflow, which peaks at a luminosity  $\sim 10^{29} - 10^{31} \text{ J s}^{-1}$  on a time scale of days.

If the star is significantly denser ( $\bar{\rho}_p/\bar{\rho}_* \lesssim 5$ ), the planet overflows its Roche lobe. For  $\bar{\rho}_p/\bar{\rho}_* \lesssim 1$  mass transfer is stable, resulting in the planet being accreted on the relatively slow time scale set by tidal dissipation. However, for an intermediate density range,  $1 \leq \bar{\rho}_p/\bar{\rho}_* \leq 5$ , mass transfer may be unstable, resulting in the disruption of the planet into an accretion disk around the star. Outflows from the super-Eddington accretion disk power an optical transient with a peak luminosity  $\sim 10^{30} - 10^{31} \text{ J s}^{-1}$  over weeks or months. Disk emission becomes visible once the accretion rate falls below the Eddington rate, resulting in a brightening and shift of the spectral peak to the ultraviolet.

The resulting transients could be distinguished from classical novae by their higher ejecta mass and lower velocity, and by hard pre-/post-cursor emission. They might be identified from nearby galaxy surveys at optical, ultraviolet, and X-ray wavelengths with cadences from days to months, with radio afterglows perhaps detectable for  $10^3 - 10^4 \text{ yr}$  (Yamazaki et al., 2017).

**Possible systems** Direct evidence for planet accretion is limited, but at least two systems may be contenders.

**V838 Mon** V838 Mon has been considered the prototype of a new stellar class with pronounced outbursts repeated at short intervals. The class comprises at least two other objects, M31RV and V4332 Sgr, with interpretations including nova-type outbursts, thermal pulses, and stellar mergers (Retter & Marom, 2003). V838 Mon underwent an unusual outburst in 2003, showing at least three peaks over a period of 100 days. Imaging revealed a light echo around the object, providing evidence for a dust shell which was emitted several thousand years ago and is now reflecting light from the eruption (Bond et al., 2003). Spectral analysis suggests that the object was relatively cold throughout the event, which was characterised by an expansion to extremely large radii. Retter & Marom (2003) suggested that the outburst was caused by the expansion of a red giant, followed by the successive swallowing of three relatively massive planets in close orbits.

Retter et al. (2006) reasoned that the similarity of the three events, each accompanied by secondary shallower peaks (Figure 7.32), rather argues for a three-step process in the accretion of a single planet into a giant stellar envelope: the captured planet reaches some critical density in the stellar envelope, triggers an initial super-Eddington event that causes the star to expand and the density of material surrounding the planet to decrease. The descent of the planet continues, and the process is repeated, until it finally reaches the nuclear burning shell at  $\sim 1R_{\odot}$ , where it dissolves or evaporates (Livio & Soker, 1984; Soker, 1998; Siess & Livio, 1999a,b).

**FH Leo** The common proper motion system FH Leo is a wide visual binary of separation 8.31 arcsec, observed together by Hipparcos as HIP 54268. It was classified as a nova-like variable due to an optical outburst observed in the Hipparcos photometry (Figure 7.33). From spectroscopy, and a study of the elemental abundances including Li and  $\alpha$ -elements, Dall et al. (2005) concluded that the component stars, HD 96273 and BD+07 2411 B, do constitute a physical binary, being of normal late-F and early-G type. At  $d = 117$  pc, the lower limit for the physical separation is 936 au.

Dall et al. (2005) concluded that the rise-time seen in the Hipparcos light curve might have been very fast, while the decay probably lasted at least 13 days, with a possible second event about 170 days later. Their favoured explanation is a planetary accretion event which resulted in an energy outburst and a polluted stellar atmosphere. From the magnitude rise, they estimated a mass of the accreted matter as  $5 \times 10^{20}$  kg, about the mass of a large asteroid. A scenario where BD+07 2411 B accreted such a companion could explain the Hipparcos outbursts, the over-abundances found in BD+07 2411 B with respect to HD 96273, and the presence of Li in BD+07 2411 B. Further analysis by Vogt (2006) has argued that FH Leo may still be a dwarf nova in a triple system.

## 7.12 Imaging at other wavelengths

### 7.12.1 X-ray and radio wavelengths

In the context of exoplanet investigations, X-ray and radio emission generally results from a variety of star-planet interactions, considered further in Section 8.10.

Radio and mm/sub-mm emission can also originate from the host star, independently of the presence of a

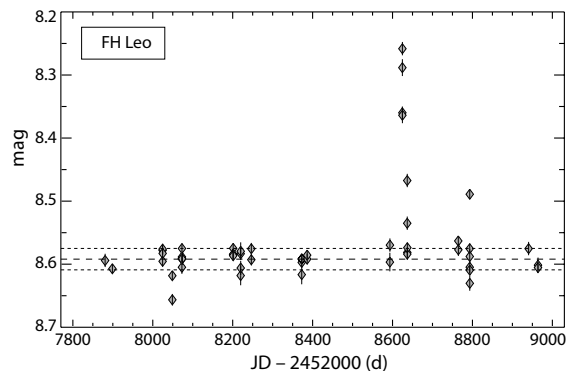


Figure 7.33: Hipparcos light curve for FH Leo. The dashed line is the mean quiescent magnitude (dotted lines are at  $\pm 1\sigma$ ). Error bars are the Hipparcos standard errors. The outburst is possibly a planetary accretion event. From Dall et al. (2005, Figure 1), reproduced with permission © ESO.

planet. High accuracy astrometry at these wavelengths can also, in principle, detect an orbiting planet through the reflex motion of the host star, as in optical astrometry. These aspects are considered in Section 3.11.

### 7.12.2 Sub-mm and mm wavelengths

**Instruments** The largest northern hemisphere facility is the  $6 \times 15$ -m element interferometer of the Plateau de Bure (IRAM, Grenoble, FRA), operational since 1988 and observing in the 3, 2, 1.8 and 0.8 mm windows, and its 12-antenna expansion NOEMA, the Northern Extended Millimeter Array (e.g. Pacheco-Vázquez et al., 2016).

In the southern hemisphere, the Atacama Large Millimeter Array (ALMA) is a mm and sub-mm interferometer consisting of  $64 \times 12$ -m antennae in the Atacama desert (northern Chile) at an altitude of 5050 m, operational since 2013 (Fomalont et al., 2015). The antennae can be spaced from a compact configuration with a minimum separation of 150 m, to a maximum spacing of 15 km, providing a resolution of 10 mas at shortest wavelengths. The receivers cover the atmospheric windows in the  $350 \mu\text{m}$ –7 mm range (35–1000 GHz) with a bandwidth of 8 GHz in two polarisations.

It was expected that ALMA would be able to image disks around young stars out to several hundred parsecs, providing density and temperature profiles through measurements of thermal dust emission, and providing information on disk dynamics and chemistry through measurements of spectral lines, as well as gaps, warps and holes caused by protoplanets (Butler et al., 2004a; Wolf & D'Angelo, 2005; Wolf, 2008).

**Imaging of disks** Since the start of full operations in March 2013, ALMA is providing detailed structural, dynamical, and chemical insights across a range of protoplanetary, transition, and debris disks (e.g. Qi et al.,

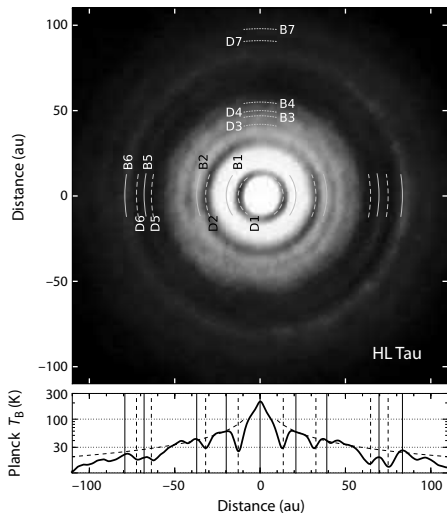


Figure 7.34: ALMA observations of the protoplanetary disk system HL Tau. Top: deprojected image at  $38 \times 19$  mas resolution. Well-modeled rings are labeled horizontally (solid and dashed lines), and less-distinct rings vertically (dotted). Bottom: cross-cut at  $138^\circ$  on a (log) Planck brightness scale (solid lines = bright rings, dashed lines = dark rings). The dashed curve shows a representative radial power law with exponent  $-0.65$ . From Brogan et al. (2015, Figure 3), by permission of IOP Publishing/AAS.

2013a; Pineda et al., 2014; Brogan et al., 2015; Casassus et al., 2015a,b). From September to late November 2014, ALMA carried out a ‘Long Baseline Campaign’ to test baselines to 15 km, demonstrating sub-mm imaging at resolutions of tens of mas (Vlahakis et al., 2015).

Science verification covered five targets, including the young protoplanetary disk system HL Tau (Jensen & Akeson, 2014; Brogan et al., 2015). Continuum images (at  $\lambda = 2.9, 1.3,$  and  $0.87$  mm, with resolutions of  $0.025\text{--}0.075$  arcsec  $\sim 3.5\text{--}10$  au), show bright and dark rings in the disk at all wavelengths (Figure 7.34). Ellipse-fitting to the most distinct rings yields the disk inclination ( $i = 46^\circ.7 \pm 0^\circ.05$ ). Additional evidence that the rings arise from planet formation include an increase in their offsets with radius, and numerous orbital resonances.

High-resolution  $880\ \mu\text{m}$  continuum images of HR 4796A resolve the 80 au radius dust ring with a characteristic width of 10 au, consistent with the narrow profile seen in scattered light (Kennedy et al., 2018).

**Imaging of planets** For exoplanet imaging, ALMA’s capabilities are more limited. At its highest resolution, it could in principle resolve a Jupiter-like planet from its host star at distances of 100–150 pc. The main limitation comes from the planetary flux. At 345 GHz, the flux density of a mature giant exoplanet is given by

$$F_{345} = 6.10^{-8} T \left( \frac{R_p}{R_j} \right)^2 \left( \frac{1}{d} \right)^2, \quad (7.4)$$

where  $d$  is the distance in pc, and  $T$  is the temperature in K. A mature Jupiter will be detectable only to about 1 pc. For a hot Jupiter with  $R = 1.5R_j$  and  $T = 1000$  K, this limit extends only to a few pc. A proto-Jupiter, with  $R = 30R_j$  and  $T = 2500$  K, would be detectable in minutes to hours out to tens of pc (Butler et al., 2004a).





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# Host stars

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PROPERTIES OF THE HOST STARS of exoplanets are derived from a combination of astrometric, photometric, and spectroscopic observations, interpreted primarily within the context of stellar evolutionary models.

Planets are now known to exist around a wide variety of stellar types, and not only around main sequence stars like the Sun. Planets have been discovered around lower-mass M dwarfs, and as low-mass companions to brown dwarfs (§7.10), around pulsating stars including hot subdwarfs (§4.3.3) and  $\delta$  Scu variables (WASP-33), around giants (§2.8.3), and around objects in the terminal stages of evolution including pulsars (§4.2) and probably white dwarfs (§4.3.2). They are found in binary systems, both circumbinary as well as circumpriary (§4.4), around stars of the thick disk (e.g. WASP-21), around stars of low-metallicity both from radial velocity surveys (e.g. Kapteyn's star, §2.9.2) and from transit surveys (e.g. WASP-37), in open clusters (§2.9.5), and perhaps in the bulge (MOA-2008-BLG-310).

Goals of improved understanding of exoplanet host stars include providing accurate absolute stellar quantities such as luminosity, mass, radius, and age, relevant to any interpretation of the relative values derived from radial velocity and transit measurements. It also provides for a deeper understanding of the conditions and dependencies relevant to planet formation.

## 8.1 Knowledge from astrometry

### 8.1.1 Hipparcos distances and proper motions

Most of the stars monitored for radial velocity observations are bright and consequently relatively nearby ( $d < 50\text{--}70$  pc). Distances and proper motions are therefore often well determined from the Hipparcos satellite measurements. Operated between 1989–93, Hipparcos provided 1 mas accuracy in positions, parallaxes and annual proper motions for about 120 000 stars (Perryman et al., 1997a,b), subsequently improved through an enhanced satellite attitude solution, outside of the formal project organisation (van Leeuwen, 2007). Transiting systems are generally more distant (even for ground-

based discoveries), typically in the distance range 100–1000 pc. Accurate geometrical parallax-based distances (Figure 8.1) translate into improved determination of the host star properties, while accurate proper motions contribute to the determination of its space motion.

The Tycho 2 catalogue (Høg et al., 2000), fully superseding the original Tycho catalogue (Høg et al., 1997), has been a further source of high-accuracy astrometric data. Together, the Hipparcos and Tycho astrometric catalogues currently provide the underlying optical reference frame for all ground-based astrometry (Perryman, 2009, Chapter 2), although this framework will, in due course, be superseded by the Gaia mission results.

**Completeness** The magnitude completeness limit of the Hipparcos catalogue ranges between  $V = 7.3\text{--}9$  mag, depending on Galactic latitude and spectral type (Perryman et al., 1997b, Volume 3, Section 3.2). Although specific efforts were made during the input catalogue compilation to ensure that all known nearby stars down to the satellite observability limit of  $V \sim 12$  were included, the catalogue is incomplete fainter than  $V \sim 7.3$  mag.

**Use in target lists** The Hipparcos data, notably the distances and derived luminosities, have been extensively used in establishing target lists for radial velocity and other planetary search programmes, for example for Keck (Vogt et al., 2002), CORALIE/HARPS (Tamuz et al., 2008) and many of the other Doppler programmes listed in Table 2.6, and more generally for studies of multiplicity of known exoplanetary systems (Raghavan et al., 2006). The Tycho 2 catalogue was used, for example, to select targets for N2K, the large-scale radial velocity survey of 2000 stars (Fischer et al., 2005).

### 8.1.2 Gaia

The Gaia satellite (§3.9) was launched in late 2013, and is scheduled to be operated until the early 2020s. Objects, predominantly stars, but including quasars, asteroids, and others, are observed at multiple epochs, with an on-board detection threshold depending only on the S/N at the epoch of observation. This yields a catalogue completeness, in the Gaia optical broad band magnitude sys-

tem,  $G \sim 20 - 21$  mag. Some 2 billion objects should be contained in the final catalogue. With expected final parallax accuracies  $\sigma_{\varpi} \sim 25 \mu\text{as}$  at  $V \sim 15$  mag, this means, for example, that a 15 mag Kepler host star at 200 pc will have a relative distance accuracy  $\sigma_{\varpi}/\varpi \sim 0.5\%$ . Qualitatively, all error bars in Figure 8.1 will fall within the plotting symbol.

Gaia will have wide-ranging impacts on fundamental stellar parameters of relevance for exoplanet host star properties, including masses and radii (e.g. Perryman, 2009; Stassun et al., 2017, 2018).

The first Gaia data release based on the first 12 months of mission data, DR1, was released in September 2016 (Gaia Collaboration et al., 2016a), and DR2 in 2018 April. Further catalogue releases are expected at regular intervals, with progressively improving accuracies, until the final catalogue sometime in the early-to-mid 2020s.

### 8.1.3 Nearby star census

The definition of the nearby stellar population figures in various areas of exoplanet research, ranging from evaluations of their statistical occurrence to the identification of nearby candidates for imaging or spectroscopy.

It remains, however, a difficult task to establish a complete census of stars within the immediate solar neighbourhood, even out to distances of only 10–20 pc. The earliest ground-based parallax surveys were very successful in identifying nearby bright stars, but problems persist at the faint end of the luminosity function,  $M_V \geq 15$ , where a complete parallax survey even out to only 10 pc remains impossible.

Surveys searching for high-proper motion stars (e.g. Luyten, 1979) were efficient at detecting nearby candidate stars which were then added to such parallax programmes (including the Hipparcos Input Catalogue in the early 1980s), but they implied a strong bias towards high-velocity halo objects. For this reason, early nearby star compilations used spectroscopic and photometric distance estimates to identify additional nearby candidates. The advent of accurate all-sky multicolour surveys further facilitated the search for nearby, low-luminosity stars.

**Catalogue of Nearby Stars** The *‘Catalogue of Stars within Twenty-Five Parsecs of the Sun’* (Woolley, 1970) was one of the first attempts to compile a census of known stars in the solar neighbourhood, largely based on trigonometric parallaxes.

An evolving compilation has been maintained by the Astronomisches Rechen-Institut in Heidelberg over the last 50 years. Gliese (1957) published the *‘Katalog der Sterne näher als 20 Parsek für 1950.0’*, containing 915 single stars and systems within 20 pc (1094 components altogether), with probable parallax errors of

9.2 mas. Gliese (1969) published the updated *‘Catalogue of Nearby Stars’*, or CNS2, with a slightly enlarged distance limit of 22.5 pc ( $\varpi \geq 0.045$  arcsec). It contained 1049 stars or systems within 20 pc, and the standard errors were estimated as 7.6 mas. In both compilations, trigonometric, photometric, and spectroscopic parallax estimates were employed.

The *‘Third Catalogue of Nearby Stars’*, or CNS3, was only published in preliminary form (Gliese & Jahreiß, 1991). This extended the census to some 1700 stars nearer or apparently nearer than 25 pc (the trigonometric parallax limit is actually 0.0390 arcsec), and was based on the latest edition of the General Catalogue of Trigonometric Stellar Parallaxes. Information includes spectral types from various sources, broad-band *UBVR* photometry, photometric parallaxes, parallaxes based on luminosity and space-velocity components, spectral type–luminosity and colour–luminosity relations, positions, and proper motions. Contrary to the CNS2, trigonometric parallaxes and photometric or spectroscopic parallaxes were not combined. The resulting parallax is the trigonometric parallax if  $\sigma_{\varpi}/\varpi < 0.14$ , or the photometric or spectroscopic parallax if the trigonometric parallax was less accurate or not available.

The *‘Fourth Catalogue of Nearby Stars’*, or CNS4, is an initiative to incorporate data from the Hipparcos Catalogue, and accordingly expected to provide a major development in the comprehensive inventory of the solar neighbourhood up to a distance of 25 pc from the Sun (Jahreiß & Wielen, 1997). The binary star content of CNS4 is discussed by Jahreiß & Wielen (2000).

**Other compilations** Additional nearby candidates are emerging from the large-scale high proper motion surveys, themselves benefiting from an astrometric recalibration of multi-epoch Schmidt plates. For example, Lépine (2005) has established, in the northern hemisphere, a list of 539 new candidate stars within 25 pc of the Sun, including 63 estimated to be within only 15 pc. He estimates that some 18% of nuclear-burning stars within 25 pc of the Sun remain to be located.

Georgia State University’s ‘Research Consortium on Nearby Stars’, RECONS (Henry et al., 2006) originally aimed to discover ‘missing’ stars within 10 pc, via astrometric, photometric, and spectroscopic techniques. On 2009 January 1, their compilation listed 354 objects in 249 systems within 10 pc, compared with 182 Hipparcos entries out to 10 pc. The survey was subsequently extended to 25 pc (Henry et al., 2011b). Since then, more than 40 papers in a series titled ‘The Solar Neighbourhood’, and using the CTIO–SMARTS 0.9-m telescope, cover: individual stars and high proper motion stars within 25 pc, including the nearest pre-main sequence star, AP Col at 8.4 pc (Riedel et al., 2011; Quanz et al., 2012b); new nearby M/L dwarfs within 10 pc (Golimowski et al., 2004); parallax distances to M stars

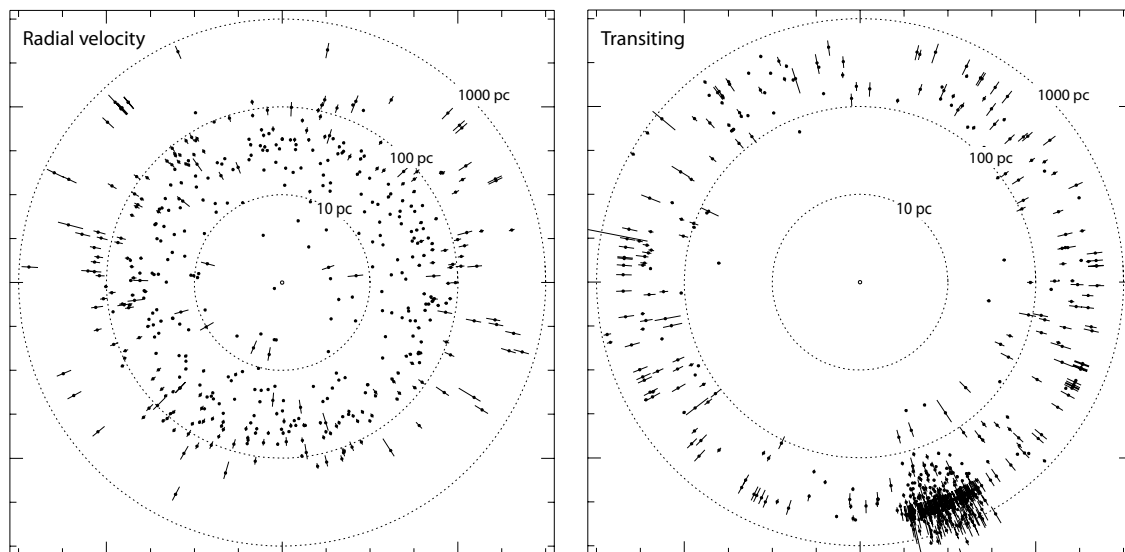


Figure 8.1: Current knowledge of exoplanet host star distances, post-Hipparcos but pre-Gaia, with all data taken from the NASA Exoplanet Archive, 2017 December 31. Left: distances, on a log scale, of all (roughly 500) radial velocity discoveries. Azimuthal coordinates correspond to right ascension, independent of declination. Host stars lie typically within 100 pc, although distances undetermined (some 20 stars) are arbitrarily assigned here to  $500 \pm 100$  pc. Right: the brightest 600 transiting systems, again with unknown distances assigned to  $500 \pm 100$  pc. Kepler targets are the cluster at the lower right. Distances, even for ground-based transit discoveries, are typically beyond 100 pc. Distances accuracies will be substantially improved by the Gaia results.

within 25 pc (Winters et al., 2015, 2017); the multiplicity fraction of nearby stars (Dieterich et al., 2012); an astrometric search for planets orbiting nearby M dwarfs (Lurie et al., 2014); and new members of a 25 pc white dwarf sample (Subasavage et al., 2007, 2008, 2009, 2017).

Other compilations of nearby stars have been undertaken (but not necessarily maintained). Northern Arizona University ‘NStars Database’, dating from 1998, maintained a compilation of all stellar systems within 25 pc, and at the end of 2010 listed around 2600 objects.

Andronova (2000) has separately compiled a catalogue of about 5000 stellar systems considered to be within 25 pc, containing data from the Hipparcos, Tycho 2, Washington Double Star, MSC, digital sky surveys and other sources.

A compilation of data for stars and planets within  $\sim 25$  pc was stated as being under development as the ‘Starchive’ (Tanner et al., 2015b).

**M dwarf surveys** Amongst nearby star surveys, particular attention has been given to M dwarfs. Among the larger surveys, a northern census of  $\sim 100\,000$  M dwarfs within 100 pc was derived from SUPERBLINK proper motions (Lépine & Gaidos, 2013). They consider the census to be  $> 95\%$  complete to 50 pc, and  $> 70\%$  complete to 100 pc. Subsamples suggested as high-priority targets for exoplanet surveys include: very bright M dwarfs amenable to high-precision radial velocity surveys, young M dwarfs making promising tar-

gets for direct/coronagraphic imaging programmes, and late-type M dwarfs with small  $R_\star$  suitable for the detection of Earth-mass planets in transit surveys. A spectroscopic catalogue of the 1564 brightest ( $J < 9$ ) M dwarf candidates in the northern sky was compiled by Lépine et al. (2013). An all-sky catalogue of 2970 bright ( $J < 9$ ) nearby ( $d < 50$  pc) M or late K dwarfs, also selected from SUPERBLINK, is given by Gaidos et al. (2014).

**Kinematic properties** In the solar neighbourhood, there is little evidence that the kinematic properties of stars with or without planets differ significantly. Barbieri & Gratton (2002) reconstructed the Galactic orbits of known host stars, and found no kinematic differences with the stars studied by Edvardsson et al. (1993). Similar results are reported by, e.g., Luck & Heiter (2006). More detailed insights can be expected from Gaia.

Ecuvillon et al. (2007) studied the kinematics of metal-rich stars with and without planets, using Hipparcos astrometry and radial velocities from CORALIE, and examined their relation to the Hyades, Sirius, and Hercules dynamical streams. Showing that the planet host targets have a kinematic behaviour similar to that of the metal-rich comparison sub-sample, and appealing to the scenarios proposed for the origin of the dynamical streams, they argued that systems with giant planets could have formed more easily in the metal-rich inner Galaxy, and then been brought into the solar neighbourhood by these dynamical streams.

## 8.2 Physical properties

The physical properties of the host stars of exoplanets are of importance in understanding many aspects of their nature, origin, and past evolution. For example, planet masses derived from radial velocity measures are expressed in terms of the host star mass, while accurate stellar radii are important for setting the linear scale of transiting planets. Models of planet formation have inferred a dependency on the host star metallicity, while stellar characteristics such as age and rotation enter more detailed system modeling. Ages provide information on the star's evolutionary state and potentially their Galactic origin, provide constraints on the processes and efficiency of resonances and tidal interactions for orbital synchronisation and circularisation, and will be important in optimising searches for exo-Earths.

This section is not intended as a comprehensive review of stellar properties and their derivation, but rather an overview of some of the most important host star characteristics in the context of exoplanet studies. It covers the topics of absolute magnitudes, effective temperatures, stellar diameters, masses and radii, and the general diagnostics used for age estimation.

Although closely related to the question of age determination, the subject of stellar rotation (with its various complications and the many new insights that have come from exoplanet studies, and in particular from Kepler) is considered separately in Section 8.3.

**Compilations** Derived from various sources and methodologies, many primary host star characteristics are tabulated in the major online compilations, notably the NASA Exoplanet Archive and the Extrasolar Planets Encyclopaedia (Table 1.4).

SWEET-Cat is an online compilation of stellar parameters, including  $T_{\text{eff}}$ ,  $\log g$ ,  $[\text{Fe}/\text{H}]$ , and  $M_{\star}$  for most planet host stars listed in the Extrasolar Planets Encyclopaedia, and largely derived using a uniform methodology (e.g. Santos et al., 2013; Sousa et al., 2015; Andersen et al., 2017).

### 8.2.1 Absolute magnitude

A star's *absolute magnitude*,  $M$ , is defined as the apparent magnitude,  $m$ , as seen at a distance of 10 pc. It is given by

$$m - M \equiv 5 \log \left( \frac{d}{10} \right) = -5 \log \omega - 5, \quad (8.1)$$

where  $d$  is in pc, or the parallax  $\omega$  is in arcsec (and where correction due to interstellar extinction is ignored). The quantity  $m - M$  is referred to as the *distance modulus*. The absolute magnitude can be expressed in any bandpass (e.g.  $M_V$ ) in terms of the apparent magnitude in that bandpass ( $m_V$  or  $V$ ).

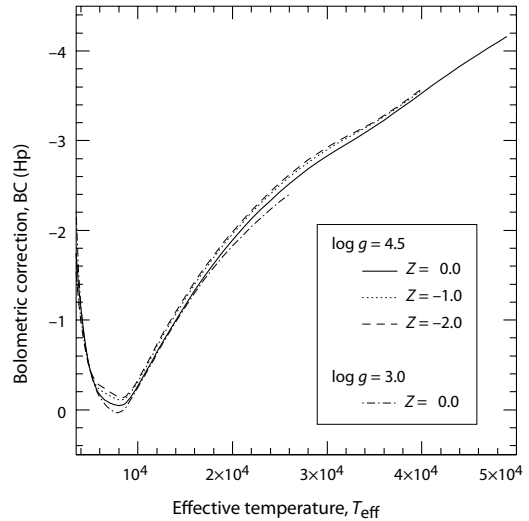


Figure 8.2: Bolometric corrections for the Hipparcos photometric passband,  $BC(Hp)$ , versus effective temperature  $T_{\text{eff}}$ , for a subset of values of  $\log g$  and  $Z$ . The determinations, by M.S. Bessell, are also available in tabular form (Bessell, 2007).

**Bolometric magnitudes** The total energy integrated over all wavelengths is referred to as the *bolometric magnitude*,  $M_{\text{bol}}$  (e.g. Gray, 2000). The quantity required to transform the absolute magnitude to the bolometric magnitude is referred to as the *bolometric correction*,  $BC$ , for that magnitude system. For example, for the  $V$  band

$$BC(V) \equiv M_{\text{bol}} - M_V = 2.5 \log \frac{\int F_V S_V dv}{\int F_V dv} + C, \quad (8.2)$$

where  $F_V$  is the measured flux, and  $S_V$  is the detector response for the relevant bandpass.  $BC$  is a function of the bandpass and the underlying stellar energy distribution of the star, the latter itself a function of  $T_{\text{eff}}$ ,  $\log g$ , metallicity, etc. The luminosity of the star is then given by

$$\log \left( \frac{L_{\star}}{L_{\odot}} \right) = -0.4 [M_V + BC - (M_{V,\odot} + BC_{\odot})]. \quad (8.3)$$

Bolometric corrections are derived from empirical calibrations or from model atmospheres. The zero point of the bolometric magnitude scale is set by reference to the Sun: Cayrel de Strobel (1996) gave  $M_{\text{bol}\odot} = 4.75$  and  $BC(V)_{\odot} = -0.08$  yielding  $M_V = 4.83$ , while Cox (2000) gives  $M_{\text{bol}\odot} = 4.74$ ,  $BC(V)_{\odot} = -0.08$ , and  $M_V = 4.82$  (see also Bessell et al., 1998);  $M_{\text{bol}\odot} = 4.75$  was adopted by IAU Commission 36 at the IAU General Assembly in 1997 (Andersen, 1999, p141).

Bolometric corrections are usually tabulated versus spectral type or colour index, and their dependence on  $B - V$  is only moderately sensitive to luminosity class. For hot or cool stars, bolometric corrections in  $V$  are large, since most of the flux lies outside of the  $V$  band.

**Bolometric corrections for Hipparcos photometry** In addition to the standard bandpasses of optical and infrared photometry, the high accuracies and uniformities of the space-based systems Kepler, and of the all-sky systems of Hipparcos and Gaia, are of specific importance.

Whenever available, and according to application, there are three compelling reasons to use the Hipparcos magnitudes  $H_p$  (van Leeuwen et al., 1997), rather than say Johnson  $V$  magnitudes as a basis for the construction of uniform bolometric magnitudes for a sample of stars: their high accuracy ( $\sigma \sim 0.0015$  mag); their small systematic errors and excellent uniformity independent of position, magnitude, and colour index; and the fact that the photometric band is very wide and therefore a better observational approximation to the total flux.

At the time of the Hipparcos Catalogue release in 1997, estimated bolometric corrections for the published  $H_p$  magnitudes were not available. This shortcoming was rectified by Bessell et al. (1998), who used synthetic spectra derived from ATLAS9 and NMACS to produce broad-band colours and bolometric corrections for a wide range of  $T_{\text{eff}}$ ,  $g$  and  $[\text{Fe}/\text{H}]$ . The same synthetic spectra were then used to construct a grid of  $T_{\text{eff}}$ ,  $\log g$  and  $Z$  giving corresponding values of the following quantities:  $\text{BC}(V)$ ,  $\text{BC}(H_p)$ ,  $V - H_p$ ,  $V - V_T$ ,  $B - B_T$ ,  $B_T - V_T$ ,  $B - V$ ,  $V - R$ , and  $V - I$  (where  $B_T$  and  $V_T$  are magnitudes in the Tycho photometric bands). The bolometric corrections are given in tabular form by Bessell (2007). Examples are shown in Figure 8.2.

### 8.2.2 Effective temperature

The *effective temperature* of a star,  $T_{\text{eff}}$ , is defined as the temperature of a blackbody radiator with the same radius and same luminosity (total energy output), related via the Stefan–Boltzmann law

$$L_{\star} = 4\pi\sigma R_{\star}^2 T_{\text{eff}}^4, \quad (8.4)$$

where  $L_{\star}$  is the luminosity,  $R_{\star}$  is the radius, and  $\sigma$  is the Stefan–Boltzmann constant. Determination of  $T_{\text{eff}}$  based on this definition therefore requires knowledge of both  $R_{\star}$  (itself requiring knowledge of the distance  $d$  and angular diameter  $\theta$ ) as well as  $L_{\star}$  (itself requiring knowledge of the star's bolometric magnitude, according to Equation 8.3).

Gray (2000) described the inaccuracy of the present knowledge of the effective temperature scale as one of the greatest barriers to the advancement of stellar evolutionary theory. Its importance in the study of exoplanets is through its role in abundance determinations, which are sensitive to the assumed  $T_{\text{eff}}$ . Calibration of the effective temperature scale via the Stefan–Boltzmann law (e.g. using the infrared flux method) has given some concordant results (e.g. Ribas et al., 2003; Sousa et al., 2008) and other discordant results (e.g. Ramírez & Meléndez, 2004, 2005a,b; Casagrande et al., 2006; Gonzalez, 2006a).

Although procedures are evidently converging, uncertainties in individual values of  $T_{\text{eff}}$  are still sometimes considered to be nearer to 100 K (Luck & Heiter, 2006).

Sousa et al. (2008) derived an empirical fit as a function of  $B - V$  given in the Hipparcos catalogue and  $[\text{Fe}/\text{H}]$

$$T_{\text{eff}} = 9114 - 6827(B - V) + 2638(B - V)^2 + 368[\text{Fe}/\text{H}], \quad (8.5)$$

with  $\sigma = 47$  K over the intervals  $4500 \text{ K} < T_{\text{eff}} < 6400 \text{ K}$ ,  $-0.85 < [\text{Fe}/\text{H}] < 0.40$ , and  $0.51 < B - V < 1.20$ .

As an example of estimating  $T_{\text{eff}}$  as a function of  $B - V$  and  $[\text{Fe}/\text{H}]$ , see Sousa et al. (2011a).

### 8.2.3 Parameters from spectroscopy

In practice, spectroscopic analysis provides robust estimates of a number of basic stellar quantities. Some examples of such analysis are noted here.

Luck & Heiter (2006) used the measured equivalent widths of some 50 Fe I and Fe II absorption lines to estimate the four basic stellar parameters which influence the relative line strengths and line profiles: effective temperature  $T_{\text{eff}}$ , surface gravity  $\log g$ , microturbulence velocity, and metallicity  $[\text{Fe}/\text{H}]$ . Typical observational requirements call for 2–3-m class telescopes, with high-dispersion échelle spectroscopy ( $R \sim 50 - 70000$ ), covering most of the optical spectrum at high signal-to-noise ratios of several hundred per resolution element.

Analyses typically make use of atmospheric models, often assuming a plane-parallel geometry (e.g. Kurucz, 1993) under the assumption of local thermodynamic equilibrium (LTE), along with basic atomic data, most critically the line oscillator strengths. Differential analysis with respect to the solar flux spectrum can employ reflectors such as the Moon (e.g. Fuhrmann et al., 1998) or Callisto (e.g. Luck & Heiter, 2006).

Further details are given in a number of the references cited below (e.g. Santos et al., 2004c; Luck & Heiter, 2006; Sousa et al., 2008; Mortier et al., 2013c; Santos et al., 2013). A somewhat different (spectrum-matching) technique was used by Valenti & Fischer (2005). In either case, typical uncertainties are in the range 0.02–0.5 dex for  $[\text{Fe}/\text{H}]$ , and 40–70 K for  $T_{\text{eff}}$  (Figure 8.3), although higher formal precision is often achieved (Kovtyukh et al., 2003).

Torres et al. (2012) derived improved and homogeneous spectroscopic parameters ( $T_{\text{eff}}$ ,  $[\text{M}/\text{H}]$ , and  $\nu \sin i$ ) for the host stars of 56 transiting planets. With a constraint on  $\log g$  based on  $\rho_{\star}$  derived from the transit light curve analysis, they could suppress systematic errors in  $M_{\star}$  and  $R_{\star}$  of up to 20% and 10% respectively, and which otherwise result in systematic errors in the derived  $M_p$  and  $R_p$ .

Many other studies have contributed to the detailed spectroscopic classification and characterisation of exoplanet host stars, and related aspects such as mass and

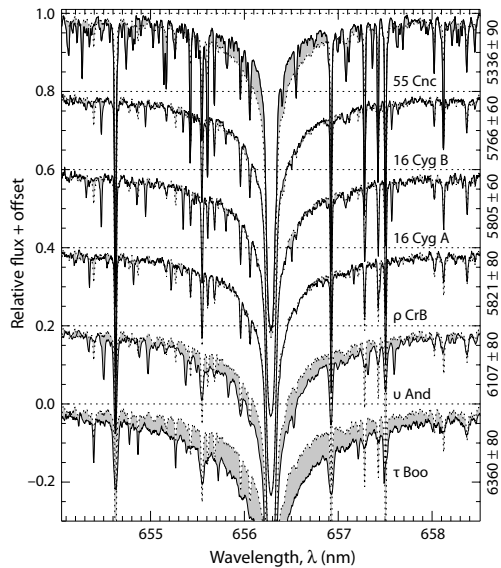


Figure 8.3:  $H\alpha$  line profiles of 55 Cnc, 16 Cyg B, 16 Cyg A,  $\rho$  CrB,  $\nu$  And, and  $\tau$  Boo. The sequence of increasing  $T_{\text{eff}}$  (given at right) is superimposed on the spectrum of the Moon for determining the instrumental profile (dotted), with differences depicted by shading. From Fuhrmann et al. (1998, Figure 1), reproduced with permission © ESO.

luminosity determination, and chemical and Galactic evolution. A number have specifically examined abundance differences in samples of stars with and without planets (e.g. Jofré et al., 2015; Buchhave & Latham, 2015; Maldonado & Villaver, 2016; Mulders et al., 2016; Mishenina et al., 2016).

Of these, Mulders et al. (2016) used 20 000 Kepler stars with metallicities from the LAMOST survey to find, amongst other more detailed correlations, an excess of hot rocky planets around metal-rich stars, in the sense that planets with  $P \leq 10$  d are preferentially found around metal-rich stars,  $[\text{Fe}/\text{H}] \approx 0.15 \pm 0.05$  dex.

Others have examined the consistency between the chemical composition of planets and their host stars (e.g. Thiabaud et al., 2015a; Gaidos, 2015).

**Abundances of other elements** Once the principal stellar parameters have been estimated, the abundances of other elements are derived from individual spectral lines using either measured equivalent widths or comparison with synthetic spectra. Abundance comparisons for stars with and without planets are usually made relative to Fe, as  $[x/\text{Fe}]$  (see box, page 389, for the meaning of the notation [...]), which removes the first-order difference in  $[\text{Fe}/\text{H}]$  between the two sample types.

Light elements such as Li, C, N, O, Na, Al, Mg, and S have relatively few spectral lines in solar-type stars, and high-quality spectra are required for reliable abundances. Some observational considerations for other specific lines are discussed by Gonzalez (2006a).

## 8.2.4 Stellar diameters

Physical stellar diameters are most typically predicted from theoretical evolutionary models. Direct measurements of stellar diameters are available for a small number of stars, and provide crucial model verification (e.g. Chiavassa et al., 2012; Boyajian et al., 2014).

Direct observational methods for determining *angular diameters* include (all with rather restricted applicability in practice) interferometry, lunar occultation, direct imaging using adaptive optics, and measurements of detached eclipsing binaries. In all cases, linear sizes follow from (preferably astrometric) distances.

Indirect estimates of stellar diameters can also be obtained using a variety of photometric or spectroscopic methods (notably based on the infrared flux method (IRFM), spectral energy distribution fitting, and surface brightness relations), generally based on the Stefan–Boltzmann relation, and proceeding via estimates of  $T_{\text{eff}}$ . As examples applied to exoplanet host stars, Ribas et al. (2003) matched 2MASS infrared photometry to synthetic photometry to estimate  $T_{\text{eff}}$  for some 80 exoplanet host stars. Fischer & Valenti (2005) derived estimates for 1040 stars from  $T_{\text{eff}}$  and Hipparcos parallaxes.

Transit light curves yield only the ratio  $R_p/R_\star$  (§6.13). While estimates of  $R_\star$  from photometry or spectroscopy are frequently very good, it is difficult if not impossible to strictly disentangle the stellar and the planetary radii. Brown et al. (2001) determined both  $R_\star$  and  $R_p$  simultaneously from a high-precision HST transit light curve of HD 209458, yielding  $R_\star = 1.146 \pm 0.050 R_\odot$ , compared with  $1.145 \pm 0.049 R_\odot$  from the star's optical-infrared energy distribution (Ribas et al., 2003).

Optical interferometers (§7.6.5) continue to yield the most direct estimates of stellar diameters (Figure 8.4), with more than 70 exoplanet host stars determined from CHARA (Baines et al., 2008, 2009; van Belle & von Braun, 2009; Boyajian et al., 2013; von Braun et al., 2014; Ligi et al., 2016). Individual stars include: Sirius A (Kervella et al., 2003); GJ 581 (von Braun et al., 2011a); 55 Cnc (von Braun et al., 2011b); GJ 436 (von Braun et al., 2012);  $\epsilon$  Eri (Baines & Armstrong, 2012);  $\kappa$  And (Baines et al., 2013); and HD 38529 (Henry et al., 2013).

An example of the joint analysis of angular diameters from interferometry, Hipparcos distances, and Kepler or CoRoT seismology are given by Huber et al. (2012a). An empirical Hertzsprung–Russell diagram for main-sequence stars with interferometrically-determined radii, including known exoplanet host stars, is given by von Braun et al. (2014, their Figure 6).

## 8.2.5 Masses and radii

Stellar properties such as mass, radius, and age are not primary observables, and are generally inferred by comparison with theoretical evolutionary models. Other

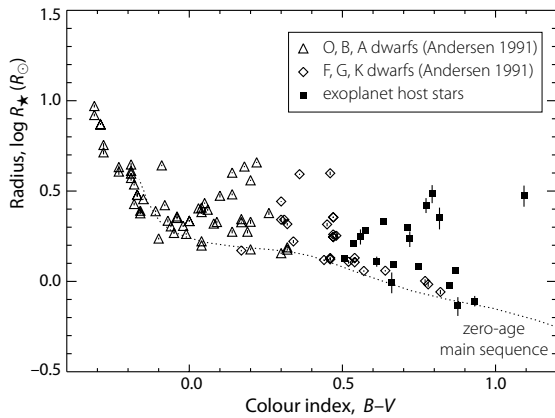


Figure 8.4: Host star stellar radii derived from interferometric angular diameter measurements with CHARA. Triangles represent O, B, and A dwarfs; diamonds represent F, G, and K dwarfs. Both sets of measurements are from Andersen (1991). Filled squares represent exoplanet host stars with errors < 15%. The dotted line is the zero-age main sequence from Girardi et al. (2000) for stars with  $M_{\star}$  in the range  $0.15 - 5.0 M_{\odot}$ . From Baines et al. (2008, Figure 3), by permission of IOP Publishing/AAS.

mass estimates can be made via orbit dynamics for binary stars, or using spectroscopic gravity indicators.

Accurate distances are essential in locating the star in the observational Hertzsprung–Russell diagram, often presented as absolute magnitude versus colour index (Figure 8.5). Theoretical evolutionary models, in contrast, are usually characterised by the bolometric magnitude ( $M_{\text{bol}}$ ) and effective temperature ( $T_{\text{eff}}$ ), and predict a star’s position in the theoretical Hertzsprung–Russell diagram on the basis of its initial chemical composition, initial mass, and assumed age.

Relating theoretical to observed quantities, and hence inferring stellar properties such as mass and age, is however subject to numerous complications. First is the choice of theoretical model, of which various well-validated examples are available and in use, and which differ in the detailed treatment of physical processes (such as line opacity, convective overshooting, and He diffusion), chemistry (such as the presence of  $\alpha$  elements), and astrophysical properties (such as rotation). To convert an observed magnitude to an absolute magnitude requires knowledge of the star’s distance (Equation 8.1), and to convert an absolute magnitude to a bolometric magnitude requires an estimate of the bolometric correction (Equation 8.2).

**Example derivations** As two early examples of the procedures that have been frequently applied subsequently in the field of exoplanets, Fuhrmann et al. (1997) used the Hipparcos parallaxes to estimate absolute magnitudes, and hence masses and ages from stellar evolutionary tracks, for 51 Peg and 47 UMa, deriving masses of  $1.12 \pm 0.06 M_{\odot}$  and  $1.03 \pm 0.05 M_{\odot}$  respectively, and ages

of  $4.0 \pm 2.5$  Gyr and  $7.3 \pm 1.9$  Gyr respectively. Fuhrmann et al. (1998) made a similar analysis for other F and G-type stars with planetary companions:  $\nu$  And, 55 Cnc,  $\tau$  Boo, 16 Cyg and  $\rho$  CrB. Figure 8.6, for the case of  $\nu$  And, typifies the difficulty of establishing metallicity unambiguously, and the improvement brought to stellar modeling by the Hipparcos results.

As an example of procedures on a larger scale, Valenti & Fischer (2005) presented a spectroscopic compilation of 1040 FGK dwarfs from the Keck, Lick, and AAT planet search programmes. They use a spectrum-matching technique that generates differences with respect to the observed spectrum that are then minimised over parameter space to simultaneously determine effective temperature  $T_{\text{eff}}$ , surface gravity  $\log g$ , projected rotational velocity  $V_{\text{rot}}$ , and metallicity [Fe/H], along with abundances of Na, the iron-peak elements Fe and Ni, and the  $\alpha$ -process elements Si and Ti. The Hipparcos parallaxes, combined with V-band photometry and corresponding bolometric corrections, were used to determine bolometric luminosities. Interpolating theoretical Yonsei–Yale isochrones (Demarque et al., 2004) with respect to  $L_{\star}$ ,  $T_{\text{eff}}$ , [Fe/H], and  $[\alpha/\text{Fe}]$  for each star then yielded a theoretical mass, radius, gravity, and age for most of their sample. Estimated precision was 44 K in  $T_{\text{eff}}$ , 0.03 dex in [Fe/H], 0.06 dex in  $\log g$ , and  $0.5 \text{ km s}^{-1}$  in  $V_{\text{rot}}$ .

A similar procedure was used by Robinson et al. (2007a) to estimate the atmospheric parameters for 1907 metal-rich stars in the N2K spectroscopic survey, based on the estimates of temperatures and metallicities for more than 100 000 FGK dwarfs from Tycho 2 (Ammons et al., 2006) or from the Geneva–Copenhagen survey (Nordström et al., 2004b).

### 8.2.6 Stellar ages

This section gives an overview of the general methods used for stellar age determination, and some top-level results on ages of exoplanet host stars. Since, however, the presence of (especially) close-in planets is now known to have an effect on stellar rotation, largely through tidal interactions, age derivation from gyrochronology becomes more complex. These aspects are therefore considered, along with the many insights into stellar rotation that have come from the Kepler mission, in the following section on stellar rotation (§8.3).

**Isochrone fitting** Stellar ages are commonly estimated by *isochrone fitting*, based on matching relevant observables to a grid of stellar evolutionary models. Typically, models generate  $T_{\text{eff}}$  as a function of either absolute stellar magnitude,  $M_V$  (e.g. Edvardsson et al., 1993; Lachaume et al., 1999), or stellar surface gravity,  $\log g_s$  (e.g. Bouchy et al., 2005b; Konacki et al., 2005).

Exoplanet studies also invoke the dependency of  $T_{\text{eff}}$

**Galaxy population synthesis models:** Various investigations benefit greatly from the availability of *Galaxy population synthesis models*, which aim to describe the observed and often very detailed properties of the Galactic stellar population using constraints from a very wide range of observations. The Bahcall–Soneira model was an important early model with wide application to studies of Galactic structure, halo modeling, and quasar evolution (Bahcall & Soneira, 1980; Bahcall, 1986, 1999).

More recent detailed models include the TRILEGAL and Besançon models. While not designed with exoplanet investigations in mind, they form a more general tool that can have important applications for exoplanet investigations. For example, Perryman et al. (2014a) used TRILEGAL to construct a detailed star count model, as a function of Galactic coordinates and magnitude, populated the stars with planets according to known distributions as a function of spectral type, planet mass, and orbital properties, and then used this simulated population to predict planets detectable with Gaia astrometry (§3.9). Prša et al. (2015) used the Besançon model to examine the stellar populations in the Kepler K2 mission extension campaigns.

**TRILEGAL:** The population synthesis Galaxy star count model TRILEGAL (TRIdimensional modeL of the GALaxy, Version 1.6, Girardi et al., 2005, 2012; Girardi, 2016) is based on a theoretical stellar luminosity function  $\phi(M, \mathbf{r}, \lambda)$  [i.e., as a function of absolute magnitude  $M$ , Galactic position  $\mathbf{r} = (\ell, b, r)$ , and photometric passband  $\lambda$ ], derived from a set of evolutionary tracks, together with suitable distributions of stellar masses, ages, and metallicities. It includes five distinct Galaxy components: the thin and thick disks, the halo, the bulge, and the disk extinction layer. The model has been calibrated with respect to a variety of observational counts, including multi-passband catalogues from deep galaxy surveys (including CDFS, DMS, and SGP), the ‘intermediate-depth’ near-infrared point source catalogue 2MASS, and the local stellar sample from Hipparcos.

A run of TRILEGAL is formally a Monte Carlo simulation in which stars are generated according to specified probability distributions. The number of stars in each distance modulus bin is predicted according to  $N(m_\lambda, \ell, b) = dm_\lambda \int_0^\infty dr r^2 \rho(\mathbf{r}) \phi(M_\lambda, \mathbf{r}) d\Omega$ . For each simulated star, the star formation rate, age–metallicity relation, and initial mass function are used to derive the stellar age, metallicity, and mass. Absolute photometry is derived via interpolation in the grids of evolutionary tracks (or isochrones), and converted to the apparent magnitudes using the appropriate bolometric corrections, distance modulus and extinction. All relevant stellar parameters can be retained from the simulations, including the initial and current mass, age, metallicity, surface chemical composition, surface gravity, luminosity, and effective temperature.

**Besançon:** The Besançon Galaxy model is a somewhat similar population synthesis model describing the observed stellar distributions (including the Tycho Catalogue) by relating them to models of Galactic formation and evolution, stellar formation and evolution and stellar atmospheres (Robin et al., 2012; Czekaj et al., 2014).

In the Besançon model, stars are ‘created’ from gas following an initial mass function and star formation rate, and evolved according to theoretical evolutionary tracks. For each simulated star, photometry, kinematics and metallicity are computed. Four main populations are assumed: a thin disk, thick disk, bulge/bar, and stellar halo, along with a 3d extinction map.

on  $(\rho_\star / \rho_\odot)^{-1/3}$ , exploiting the fact that  $\rho_\star$  can be well-constrained through transit photometry (§6.13.7).

Although isochrone fitting is in principle applicable to stars across the Hertzsprung–Russell diagram, derived ages typically have a precision that varies significantly according to location (e.g. Jørgensen & Lindgren, 2005). Thus, age determination for spectral types later than mid-to-late G is complicated by their very slow evolution, with nuclear burning time scales longer than the age of the Galactic disk. The complex shape of isochrones close to the main-sequence turn-off can also pose problems, as can interpolation between isochrones of non-uniform spacing (Soderblom, 2010).

**Gyrochronology** Stellar ages are frequently estimated from their rotational velocities or periods through *gyrochronology*. Unlike isochrone fitting which draws on absolute magnitudes, gyrochronology does not rely on accurate stellar distances. The method was founded on observations which showed that, by the age of the Hyades, stellar rotation in open clusters tends to converge to a single period–colour–age relation. Suggested by Barnes (2003), it builds on the period–age relationship described by Skumanich (1972). Barnes (2003) adopted a relation of the form

$$P_{\text{rot}} = A^n \times a(B - V - c)^b, \quad (8.6)$$

where the rotation period  $P_{\text{rot}}$  is in d,  $A$  the age in Myr, and  $B$  and  $V$  are Johnson magnitudes. Different fits for the dimensionless free parameters  $a$ ,  $b$ ,  $c$ , and  $n$  have been reported (e.g. Barnes, 2003; Mamajek & Hillenbrand, 2008; Meibom et al., 2011b; Angus et al., 2015), and are compared in Angus et al. (2015, their Table 1).

Calibrations extending to the 2.5 Gyr aged cluster NGC 6819 were derived by Meibom et al. (2015). From 11 Kepler planet host stars with ages more than 2 Gyr, Ceillier et al. (2016) confirmed extension of the age–rotation correlation to the oldest Kepler stars.

Its theoretical basis rests on the fact that during the pre-main sequence phase, angular momentum evolution is mainly driven by the magnetic coupling between the star and its disk, with solar-type stars arriving on the zero age main sequence with a large spread in rotation (e.g. Königl, 1991; Epstein & Pinsonneault, 2014). From this point on, angular momentum evolution is dictated by stellar winds whose intensity is itself a function of magnetic activity and rotation (e.g. Kawaler, 1988). This creates a regulation mechanism leading to a steady rotational decrease, and to the convergence of the rotation rate at about 1 Gyr.

Further developments (Barnes, 2007b) suggest that, while not calibrated for hot, rapidly rotating early-type stars, it can provide ages with an accuracy of 10% for



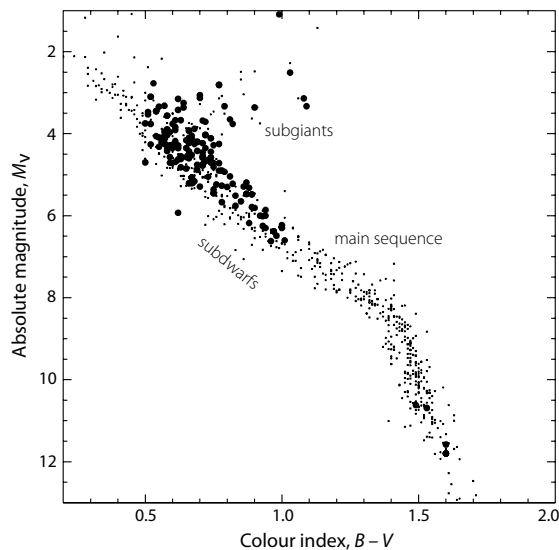


Figure 8.5: The Hipparcos-based Hertzsprung–Russell diagram for stars within 25 pc from the sample of Reid et al. (2002), with systems identified with planetary companions shown as filled circles. Adapted from Hawley & Reid (2003, Figure 3), to reflect the status as of mid-2007, by Neill Reid.

FGK and M spectral types (Mamajek & Hillenbrand, 2008; Collier Cameron et al., 2009a; Delorme et al., 2011). Studies of Li abundances (§8.4.7) further suggest that angular momentum transfer arising from long-duration star–disk interactions during the pre-main sequence phase may have resulted in yet systematically slower stellar rotation rates at the beginning of the star’s main sequence evolution for some planet host stars.

Angus et al. (2015) combined 310 Kepler stars with asteroseismic ages, 50 from the Hyades and Coma Ber clusters, and 6 field stars, to calibrate their best fit to Equation 8.6 which, with  $c = 0.45$ , are  $a = 0.40^{+0.3}_{-0.05}$ ,  $b = 0.31^{+0.3}_{-0.02}$ , and  $n = 0.55^{+0.02}_{-0.09}$ , although they stress that no single relation between rotation period, colour and age can adequately describe all the data.

Other specific results on ages of Kepler stars are detailed in Section 6.29.5.

**Other age indicators** Asteroseismology (§8.6) provides age estimates linked to stellar evolutionary models through proxies such as central H/He abundance and constraints from estimates of internal rotation (e.g. Aerts, 2015; Silva Aguirre et al., 2015). The latter, for example, quotes age uncertainties of 14% for 33 Kepler hosts with well-determined pulsation frequencies.

Chromospheric activity provides a reliable age indicator for solar-type stars from young ages to about 1 Gyr (Sestito & Randich, 2005), or perhaps even to the age of the Sun (Wright et al., 2004a).

Lower limits are sometimes inferred from lithium abundances as a function of effective temperature based

on calibrations using clusters of different ages (Martin, 1997; Jeffries et al., 2002; Sestito & Randich, 2005), or from the Ca II activity–age relation (Henry et al., 1996; Pace & Pasquini, 2004; Wright et al., 2004a).

For transiting planet host stars, the stellar density  $\rho_*$  can often be determined directly from the transit light curve (Equation 6.22), which can then be combined with observations to estimate its mass and age by comparison with stellar models (e.g. Maxted et al., 2015a; Bonfanti et al., 2016).

**Ages of exoplanet host stars** As a class, exoplanet host stars appear to show no very strong departures from the typical ages of stars in the solar neighbourhood.

Saffe et al. (2005) used chromospheric activity and isochrones to derive median ages of 49 host stars of  $5.2 \pm 4$  Gyr and  $7.4 \pm 4$  Gyr respectively. Similar median ages were derived for transiting-planet host stars through isochrone fitting by Bonfanti et al. (2016).

Reid (2002) used a control sample of 486 Hipparcos FGK stars to show that the planet host stars exhibit velocities with a lower dispersion than field stars, suggesting that their average age is only some 60% that of a representative subset of the disk. This may reflect the higher proportion of metal-rich stars in the planet sample.

Reid et al. (2007) used the data of Valenti & Fischer (2005) to demonstrate that, while the age distribution of nearby FGK dwarfs is broadly consistent with a uniform star-formation rate over the 10 Gyr history of the Galactic disk, most stars known to have giant planetary companions are, in contrast, younger than 5 Gyr. Systems with star–planet separations  $< 0.4$  au have a significantly flatter age distribution, suggesting that they are dynamically stable on time scales of many Gyr. If the frequency of terrestrial planets is furthermore correlated with stellar metallicity (§8.4), then the median age of such planetary systems is likely to be around 3 Gyr.

Melo et al. (2006) examined the ages of five stars hosting very short orbital period ( $P < 3$  d) transiting planets, to establish whether their non-detection in radial velocity surveys is due, as a class, to them being rapidly evaporated due to a high ultraviolet flux of their (presumably young and hot) host stars. From their chromospheric activity indices, none were found to be younger than 0.5 Gyr.

### 8.3 Stellar rotation

**Introduction** The study of stellar rotation is important in understanding many of the fundamental properties of stars, including the origin and evolution of the rotation itself, the origin and evolution of stellar angular momentum, and the role of rotation in stellar magnetism and in the mixing of chemical elements. Rotation also provides the basic ingredient for stellar age determination based on gyrochronology (§8.2.6).

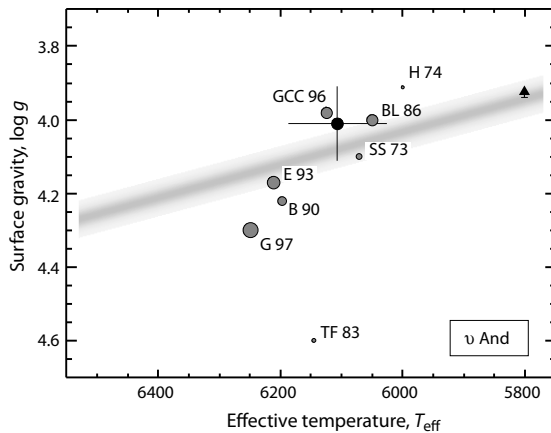


Figure 8.6:  $\log g$  versus  $T_{\text{eff}}$  for  $\nu$  And. The black circle, with error bars, marks the spectroscopically derived values. The inclined greyscale bar indicates the most probable parameter space allowed by the accurate Hipparcos distance. Grey circles represent results from earlier work, with diameters proportional to derived metallicity. A systematic shift of the bar as a result of different metallicity scales is indicated by the vertical arrow for a decrease in  $[\text{Fe}/\text{H}]$  by 0.1 dex. From Fuhrmann et al. (1998, Figure 2), reproduced with permission © ESO.

For exoplanet host stars in particular, rotation enters the studies of tidal interactions between close-in planets, and can be used to confirm the reality of some planets by demonstrating that the period radial velocity signature is distinct from the host star's spin period.

On the (often erroneous) assumption that the stellar rotation axis is aligned with the planet's orbital axis, rotation can be used to estimate masses of Doppler detected planets (by removing the  $\sin i$  discrepancy) by determining the line-of-sight inclinations of the stellar rotation axes, based on the projected equatorial velocity,  $\nu \sin i$ , the stellar rotation period,  $P_{\text{rot}}$ , and the stellar radius,  $R_{\star}$  (e.g. Simpson et al., 2010a; Watson et al., 2010).

More robustly, rotation enters the determination of orbital obliquities for transiting planets via the Rossiter-McLaughlin effect (§6.18), or from the patterns of star spot occultations (§6.14.2).

Stellar rotation is also important in considering biases in target selection. For example, because of the general decrease of rotational velocity with increasing stellar age (§8.2.6), target selection for radial velocity surveys according to low rotation or activity will result in a planet host sample skewed toward older stars.

A substantial body of information on differential stellar rotation has followed from the Kepler results, where accurate photometry frequently yields not only rotation rates from the rotational modulation of star spots, but insights into differential rotation as a result of their latitudinal dependence.

### 8.3.1 Diagnostics of rotation

Stellar rotational velocities can be determined from the (rotational) broadening of spectral lines. Rotation *periods* can also be estimated from the periodicity of various photometric and spectroscopic indicators (e.g. Barnes, 2001). Noteworthy in the context of the very large numbers of stars monitored photometrically at high accuracy and cadence by Kepler is the recurrence patterns of star spots (§6.14.2), although not all periodicities are due to rotation, and the most significant period is not necessarily the rotation period (e.g. Basri et al., 2011).

In solar-like stars, which comprise the majority of Kepler targets, much of the variability is due to magnetic activity: star spots and active regions on the stellar surface modulate the brightness on the rotation time scale of the star. Since the generation of the star's magnetic field is intimately tied to (differential) stellar rotation (e.g. Parker, 1975), measurement of variability yields rotation periods, insights into differential rotation, and feedback to theories of magnetic field generation in both solar-like and other stars.

As well as being used to quantify rotation for solar-type stars, quantitative measures of modulated light curves can be used as proxies of magnetic activity. He et al. (2015) describes two complementary measures which depict different aspects of magnetic activities: the autocorrelation index  $i_{\text{AC}}$ , which describes the degree of periodicity of the light curve, and the effective fluctuation range of the light curve  $R_{\text{eff}}$ , which reflects the depth of rotational modulation.

**Early studies** In one of the first such studies for exoplanet host stars, Barnes (2001) compared the rotation periods of 11 exoplanet host stars, derived through photometric or spectroscopic variability indicators, with comparison stars, and results from evolutionary stellar models. One motivation was to seek evidence for any rotational signature of star-disk interaction that might be useful in discovering new systems.

In contrast, the analysis suggested no statistical differences in underlying stellar rotation between the host stars of extrasolar planets and normal solar-type stars. In their sample, just one host star,  $\tau$  Boo, suggested tidal spin-up, while some 10 systems indicate orbital circularisation. The study also emphasised the scarcity of measured rotation periods for planet hosting stars, and the limited information on their ages.

Gonzalez (2008) suggested that the  $\nu \sin i$  values of stars with planets are smaller than those of stars without planets for stars cooler than 6000 K, nearly the same for stars near 6000 K and much larger for the hottest stars. For 147 exoplanet host stars, Alves et al. (2010) confirmed the general trend of rotational velocities for intermediate to lower main sequence stars, with a sudden decline near (late F)  $1.2M_{\odot}$  (Kraft, 1967), but with no statistical difference in  $\nu \sin i$  between stars with planets

and those without. However from a near-final sample of Kepler stars, Gonzalez (2015b) found that KOI stars with planets do rotate more slowly than those without known planets, behaviour extending to stars with planets of all types, not just stars with giant planets.

Various programmes have been directed at the measurement of stellar rotations, both as an input to candidate selection for planet search programmes, and for further characterisation of exoplanet host stars. These include spectroscopic rotational velocities for 1040 stars from the SPOCS FGK dwarf survey (Valenti & Fischer, 2005); spectroscopic rotational velocities of 56 M dwarfs with HET (Jenkins et al., 2009b); rotation periods of 10 exoplanet hosts from their Ca II emission (Simpson et al., 2010a); rotation periods, in the range  $P = 0.25 - 100$  d, for nearly 2000 solar neighbourhood field stars from the CoRoT data (Affer et al., 2012); and rotational periods in the Praesepe cluster (Kovács et al., 2014).

Lanza (2010) found that plotting  $P_{\text{rot}} t^{-\zeta}$  as a function of  $T_{\text{eff}}$  for planet-hosting stars gives a poor fit to the period–colour relation of Barnes (2007b), and that the rotation periods of hot Jupiter hosts were, on average, a factor of 0.7 faster than non-planet-hosting stars. For 68 host stars, Brown (2014a) investigated whether tidal interactions led to underestimated ages using gyrochronology, and found only a weak dependency.

**Rotation from Kepler** Amongst specific analyses of Kepler data (see also §6.29.5) studies have reported: • rotation periods, derived from star spots (and well correlated with archival  $v \sin i$  data), of 12 000 Kepler field stars as a function of (FGKM) spectral type, including 795 M stars (Nielsen et al., 2013b); • rotation periods and ages for 950 Kepler stars (Walkowicz & Basri, 2013); • rotation periods, derived from star spots, for 24 000 Kepler field stars (Reinhold et al., 2013); • rotation periods, derived from star spots, for an independent sample of 1919 main sequence Kepler (KOI) stars, with 737 robust periods (McQuillan et al., 2013b); and an enlarged sample of 133 030 main sequence Kepler targets yielding 34 030 star-spot derived rotation periods over 0.2–70 d (McQuillan et al., 2014); • rotation periods of A-type stars in the Kepler field (Murphy, 2014); • rotation periods for 17 rapidly rotating giant stars, with  $P_{\text{rot}}$  in the range 13–55 d, demonstrating rotation at up to 18 times the rotation period of the Sun (Costa et al., 2015); • rotation periods of solar-type stars from Kepler and CoRoT showing bimodality in age around 1 Gyr with a 70–30% slit between young and old (Leão et al., 2015); • rotation periods for 18 500 stars, 12 300 showing differential rotation, gyrochronology ages for 17 000, and showing a bimodal age distribution for  $T_{\text{eff}}$  between 3200–4700 K (Reinhold & Gizon, 2015); and • rotation periods for 11 Kepler stars older than 2 Gyr (Ceillier et al., 2016).

More generally, rotation and star spot occurrence has been quantified for a range of spectral types, includ-

ing 1570 M dwarfs (McQuillan et al., 2013a; Dmitrienko & Savanov, 2017; Koen, 2018), and 2846 solar-type stars (Savanov & Dmitrienko, 2017), along with studies of star spot life times with respect to light curve amplitude and spectral type (Giles et al., 2017).

Davenport (2017) used Gaia Data Release 1 to isolate 1299 bright rotating stars from Kepler with good astrometry. The 894 lying near the main sequence show a bimodality in rotation period, centred around a 600 Myr rotation isochrone. This feature matches the bimodal period distribution found in cooler stars with Kepler, but was previously undetected for solar-type stars due to sample contamination by subgiants.

**Long-term variability** While the origin of the 11-year solar activity cycle remains an unsolved question in solar and stellar physics, it is well established that, through the emergence and decay of (dark) sun spots and (bright) faculae, the magnetic cycle of the Sun is accompanied by brightness variations. More generally, it has been suggested that the period of the stellar activity cycle increases with rotation period (a review of this field is given by Reinhold et al., 2017, their Section 1).

While the Kepler mission was primarily optimised to detect small short-duration signals rather than long-term trends, long-term variability can be recovered from the Kepler ‘full-frame images’, calibration data collected monthly. An open source package for this, `f3`, was developed and made available by Montet et al. (2017a). They applied it to demonstrate long-term photometric variability in 10% of 4000 solar-type stars with measured rotation periods. Similar detailed studies were made by Mehrabi et al. (2017).

Reinhold et al. (2017) analysed 23 601 Kepler stars, and detected amplitude periodicities in 3203 stars between  $0.5 < P_{\text{cyc}} < 6$  yr covering rotation periods between  $1 < P_{\text{rot}} < 40$  d. Their measurements demonstrate that the cycle period shows a weak dependence on rotation rate, slightly increasing for longer rotation periods, but do not support the existence of distinct sequences in the  $P_{\text{rot}} - P_{\text{cyc}}$  plane. The total mission duration was too short to draw firm conclusions on activity cycles with similar lengths to that of the solar cycle.

**Tidal effects** Age estimation by gyrochronology (§8.2.6) assumes that stellar rotation evolves by magnetic braking alone. However, in both binary systems and hot Jupiter systems, tidal torques can dominate the natural spin-down, with tidal spin-up of the star resulting from angular momentum deposited by inwardly-migrating massive planets (§10.11.8). Various studies have suggested that these tidal interactions may be responsible for discrepancies between isochronal and gyrochronological age estimates.

Tidal interaction and evolution is considered further in Section 8.3, although some of the findings relevant to age estimation and stellar spin rates are included here.

Anomalous rotation rates may also be expected as a result of giant planet ingestion during the expanding star’s red giant, horizontal branch and early asymptotic branch phases (Massarotti, 2008).

From their Kepler sample, McQuillan et al. (2013b) compared stellar periods to the orbital periods of the

system's innermost planet. They found (without identifying a specific mechanism) a notable lack of close-in planets around rapid rotators, in the sense that only slowly spinning stars with rotation periods  $\geq 5 - 10$  d host planets on orbits shorter than 2–3 d. Bimodality observed in the period–temperature distribution for M dwarfs was confirmed by McQuillan et al. (2014). Tests of the statistical Chandrasekhar relation for the consistency of  $\langle v \rangle$  and  $\langle v \sin i \rangle$  were reported by Silva et al. (2014).

For 28 transiting exoplanet host stars with measured rotation periods, Maxted et al. (2015b) found that the gyrochronological age is significantly lower than the isochronal age for about half the stars, and that star-planet tidal interactions provide a reasonable explanation for the discrepancy in some but not all cases (which remain unexplained). For example, a particularly significant discrepancy exists for the young age for CoRoT-2 estimated from either gyrochronology or its high Li abundance, and the extremely old age for its K-type stellar companion inferred from its very low X-ray flux. The discrepancy does not necessarily indicate evidence for tidal interactions.

### 8.3.2 Obliquities

The *obliquity*, or axial tilt, is the angle between an object's rotation axis and its orbital axis, or, equivalently, the angle between its equatorial and orbital planes. The term is used to describe both the tilt of a planet (planet obliquity), or that of a star (stellar obliquity), with respect to some orbital plane. Consideration of obliquities occurs in many areas of exoplanet studies. This section provides an overview, and pointers to related sections.

**Planet obliquities** A planet's obliquity is the angle between its axis of rotation and the direction perpendicular to some reference (orbital) plane. In the solar system, planet obliquities range between the extremes of  $0^\circ.03$  for Mercury to  $177^\circ$  for Venus, and they contribute to tracing its formation history (§12.4.6).

Planet obliquities tend to vary slowly with time, both because of the planet's axial precession (due to torque exerted by the star on a planet's equatorial bulge), and because of changes in the planet's orbital plane due to the influence of other planets. Specifically, Earth's tilt, referred to as the *obliquity of the ecliptic*,  $\epsilon$ , evolves both due to precession, and to variations in Earth's orbital (or ecliptic) plane (box, page 260), and is partly stabilised by the Moon (§12.3.3). Earth currently has an axial tilt of about  $23^\circ.4$ , decreasing by  $\sim 0.47$  arcsec  $\text{yr}^{-1}$ .

There are presently no conclusive observational data on *exoplanet* obliquities, although various prospective techniques have been considered. These include: exploiting a planet's rotational flattening, for example from the difference in ingress and egress profiles during transits (§6.14.7); through modeling of (asymmetric)

orbital phase curves attributable to inhomogeneous cloud cover (§6.15.7); and by measuring the Rossiter–McLaughlin effect at secondary eclipse (§6.18.5).

**Stellar obliquities** The stellar obliquity,  $\psi_*$ , refers to the axial tilt of the star with respect to the orbital plane of (one or more of) its planets, and it represents a substantial topic of investigation.

In the solar system, the rotation axis of the Sun is tilted by  $\sim 7^\circ$  with respect to the mean planetary orbit plane, and by  $\sim 6^\circ$  with respect to the total angular momentum, or 'invariable plane'. There is no definitive explanation for this significant axial tilt (§12.1.5).

In general, and particularly for small spin–orbit misalignments (and as is the case for the Sun), it will not be evident whether the planet orbit(s) have evolved to be misaligned with the rotation axis of the host star, or whether the stellar spin axis has evolved to be misaligned with respect to the planetary orbit(s), or even whether the stellar photosphere is rotating differentially with respect to its interior (§10.10.7).

A significant number of exoplanet systems have very large obliquities, implying that the planet orbits in a plane highly misaligned with the rotation axis of the host star. Specifically, hot Jupiters are found with a wide range of obliquities, including orbits that are highly inclined, polar, or even retrograde. This is interpreted as evidence that inward migration is often driven by multi-body interactions, rather than through the gas disk. Measurements of stellar obliquities therefore provide valuable observational constraints on the planetary environment at formation, the architecture of planetary systems, and the processes that drive evolutionary changes in them (§6.18.8).

**Determination of stellar obliquity** While direct measurement of the obliquity is problematic, various techniques allow for precise measurement of its projection on the plane of the sky,  $\lambda$ , which is a lower limit to the true obliquity,  $\psi_*$  (Figure 6.69). These include the Rossiter–McLaughlin effect, exploiting the fact that different parts of a rotating star surface are progressively occulted by a transiting planet (§6.18); the use of star spots as diagnostics of stellar rotation and constraints on obliquities (§6.14.2); constraints through asteroseismology (§6.29.7); transit light curves across a non-uniform, oblate, rapidly rotating stellar disk (§6.14.3); and Doppler tomography (§6.18.6).

Obliquities have been derived in a few other more specific cases. In the Fomalhaut system, observations of the stellar rotation and disk geometry were used to constrain the alignment, without reference to the planet subsequently inferred to occupy the disk (Le Bouquin et al., 2009). The effects of rotational Doppler beaming, a photometric Rossiter–McLaughlin-type effect, has also been used (Groot, 2012; Shporer et al., 2012).

Obliquities are also discussed in the context of results from Kepler (§6.29.6), mutual inclinations of multi-planet systems (§6.30.5), and tides (§10.11.11).

**Constraints on true obliquity** The true (‘deprojected’) angle between the stellar rotation axis and the planet orbit,  $\psi \geq |\lambda|$  (Figure 6.69), is given geometrically in terms of  $\lambda$  by (Winn et al., 2007c, eqn 7–8)

$$\cos \psi = \cos i_{\star} \cos i + \sin i_{\star} \sin i \cos \lambda, \quad (8.7)$$

where  $i$  is the orbit inclination (given by transit photometry),  $i_{\star}$  is the inclination of the stellar rotation axis ( $90^{\circ}$  if the stellar rotation axis is orthogonal to the line-of-sight, and  $0^{\circ}$  if the star is seen pole-on), and  $\lambda$  is the angle between the sky projections of the two axes (as given by, e.g., the Rossiter–McLaughlin effect).

Determination of  $i_{\star}$  is not straightforward, and various approaches have been used to estimate it, and hence  $\psi$ . One is to determine the line-of-sight rotational velocity of the star,  $v \sin i_{\star}$ , either (conventionally) from the width of photospheric absorption lines, or from the Rossiter–McLaughlin effect itself (Ohta et al., 2005; Giménez, 2006b). The observed  $v \sin i_{\star}$  can then be compared with an independent estimate of the equatorial velocity of the star,  $v$ , to yield  $i_{\star}$ . Schlaufman (2010), for example, used an empirical relation for Sun-like stars to evaluate  $v$  from their masses and ages.

Alternatively, the stellar spin period,  $P_{\text{rot}}$ , can be estimated photometrically from periodic variations in the light curve whenever there are magnetic surface features that rotate into and out of view (some ambiguity arises due to the effects of differential rotation, given that the dominant feature will be located at some unknown latitude, cf. box, page 213). For moderately active stars, many such rotation periods have been derived from star spot modeling of the high-accuracy CoRoT (e.g. Mosser et al., 2009) and Kepler observations (§6.14.2).

The value of  $i_{\star}$  then follows from (e.g. Winn et al., 2007c, eqn 4)

$$\sin i_{\star} \equiv \frac{v \sin i_{\star}}{v} = v \sin i_{\star} \left( \frac{P_{\text{rot}}}{2\pi R_{\star}} \right), \quad (8.8)$$

where  $v \sin i_{\star}$  is determined from spectroscopic observations, and  $R_{\star}$  from transit observations.

For late-type stars,  $i_{\star}$  can be determined from asteroseismology, exploiting the fact that stellar rotation affects the frequency spectrum of the stellar oscillation modes (e.g. Gizon & Solanki, 2003; Ballot et al., 2006). Stellar rotation induces a multiplet fine structure, whose frequency separation for each mode is dependent on the internal rotation profile of the star as well as the stellar structure, for each mode. The apparent profiles of the rotationally-induced frequency multiplets are sensitive to the inclination of the stellar rotation axis with respect to the line-of-sight,  $i_{\star}$ .

The first star with a measured rotation period that also has a transiting planet, and the first determination of  $\psi$ , was reported for HD 189733 by Winn et al. (2007c). Photometric variability from the Fairborn APT telescope, and attributed to star spots, gave  $P_{\text{rot}} = 13.4 \pm 0.4$  d, and an upper bound of  $\psi < 27^{\circ}$ .

Of more than 100 transiting hot Jupiters with estimates of  $\lambda$  (compiled in TEPCAT, §6.18.7), some 30 transiting systems currently have individual estimates of  $\psi$ .

For lower mass planets, Winn et al. (2017a) identified 156 planets hosts with both  $v \sin i$  and rotation period known, finding nearly all to be compatible with high inclination, and hence low ( $\lesssim 20^{\circ}$ ) obliquity. Their results support the developing picture that Kepler planet-hosting stars generally have low obliquities, with the exception of hot stars hosting hot Jupiters.

Even with accurate measures of  $P_{\text{rot}}$ , only rather weak constraints on  $i_{\star}$  ( $\sim 10^{\circ}$ ) have generally been possible due to uncertainties on  $R_{\star}$  and, for slow rotators, on  $v \sin i_{\star}$ . Furthermore, because the sine function flattens near  $90^{\circ}$ , obliquities for well-aligned systems are less precise, with the method being most effective for identifying misaligned orbits. Quinn & White (2016) have shown how the combination of bright star transiting systems from CHEOPS and TESS, distances from Gaia, and stellar angular diameters ground-based interferometry will lead to improved estimates of  $i_{\star}$ .

Crida & Batygin (2014) provide the probability density function of  $\lambda$  knowing that of  $\psi$ .

### 8.3.3 Differential rotation

**The Sun** The Sun’s angular velocity  $\Omega$  depends on the latitude  $\theta$ , with the equatorial region rotating faster than the poles. Such latitudinal *differential rotation* can be described by (Reinhold et al., 2013, eqn 1)

$$\Omega(\theta) = \Omega_{\text{eq}}(1 - \alpha \sin^2 \theta), \quad (8.9)$$

where  $\Omega_{\text{eq}}$  is the equatorial angular velocity, and  $\alpha$  is the relative horizontal shear ( $\alpha > 0$  describes solar-like differential rotation,  $\alpha < 0$  describes anti solar-like, and  $\alpha = 0$  describes rigid body rotation;  $\alpha_{\odot} = 0.2$ ). The absolute shear  $\Delta\Omega$  between equator and poles is then

$$\Delta\Omega = \Omega_{\text{eq}} - \Omega_{\text{pole}} = \alpha \Omega_{\text{eq}}. \quad (8.10)$$

Differential rotation is considered to be a major driving mechanism in the generation of stellar magnetic fields.

The Sun’s (differential) rotation can be derived from various ‘tracer’ features on its surface, including sun spots, as well as via helioseismology. A comparison of results obtained by the different techniques of Doppler shift, Doppler feature tracking, magnetic feature tracking, and p-mode splittings, is given by Beck (2000).

Determination from variations in the *total solar irradiance* and *spectral solar irradiance* from the space-based SOHO–VIRGO instrument has also been demonstrated (Lanza et al., 2004; Paz-Chinchón et al., 2015).

**Asteroseismology** Apart from the Sun, for which surface features can be resolved, observations of stellar differential rotation is more problematic. Over the past decade, measurements and insights have advanced significantly through asteroseismology (§8.6).

**Kepler targets** Significant new (surface) measurements have been provided by Kepler. Compared with the simple case of a single star spot, multiple co-rotating spots at different latitudes on an active stellar surface generate more complex periodic variability signatures. These have been shown to provide a valuable proxy for measuring surface differential rotation.

Reinhold & Reiners (2013) described a method to characterise differential rotation for suitable stars in the Kepler field. This exploits their finding that the most significant period from a star spot analysis was on average 2.4% less than the true rotation rate, while differential rotation was evident from a second period close to it.

Applied to 40 661 Kepler stars from Q3, Reinhold et al. (2013) found 24 124 rotation periods ( $P_1 = 0.5 - 45$  d), and a second within  $\pm 30\%$  of  $P_1$  in 18 616 (77%). Attributing these to differential rotation, they found that the relative shear  $\alpha$  increases with  $P_{\text{rot}}$ , and decreases with  $T_{\text{eff}}$ . The absolute shear  $\Delta\Omega$  increases from  $\Delta\Omega = 0.079 \text{ rad d}^{-1}$  at  $T_{\text{eff}} = 3500 \text{ K}$  to  $\Delta\Omega = 0.096 \text{ rad d}^{-1}$  at  $T_{\text{eff}} = 600 \text{ K}$ . Above 6000 K,  $\Delta\Omega$  shows a larger scatter. The dependence of  $\Delta\Omega$  on  $P_{\text{rot}}$  is weak over a large period range. The resulting picture of stellar surface shear is consistent with theoretical predictions (e.g. Küker & Rüdiger, 2005, 2011; Hotta & Yokoyama, 2011).

Reinhold & Gizon (2015) derived  $P_{\text{rot}}$  for 18 500 stars, mostly in agreement with McQuillan et al. (2014). They found 12 300 showing differential rotation, derived gyrochronology ages for 17,000, and showed that there is a bimodal age distribution for  $T_{\text{eff}}$  between 3200–4700 K. A 2-spot model applied to solar-type stars yielded further details for 17 stars (Das Chagas et al., 2016).

**Individual Kepler planet hosts** Amongst these large-scale programmes, planet hosts include Kepler–81 and Kepler–248 (see also Savanov, 2011b), and Kepler–17 (see also Bonomo & Lanza, 2012).

Differential rotation has also been inferred for other individual Kepler stars, either via spot modeling (Frasca et al., 2011; Fröhlich et al., 2012), or through light-curve inversion that yields a map of surface temperature (Savanov & Dmitrienko, 2011; Savanov, 2011a,b; Savanov & Dmitrienko, 2012; Roettenbacher et al., 2013).

### 8.3.4 Angular momentum

**The solar system** A notable feature of the solar system, and one intimately linked to its formation, is the *angular momentum problem*: the fact that while the Sun has some  $10^3$  times more mass than all the solar system planets combined, it has only 0.3% of the system's total

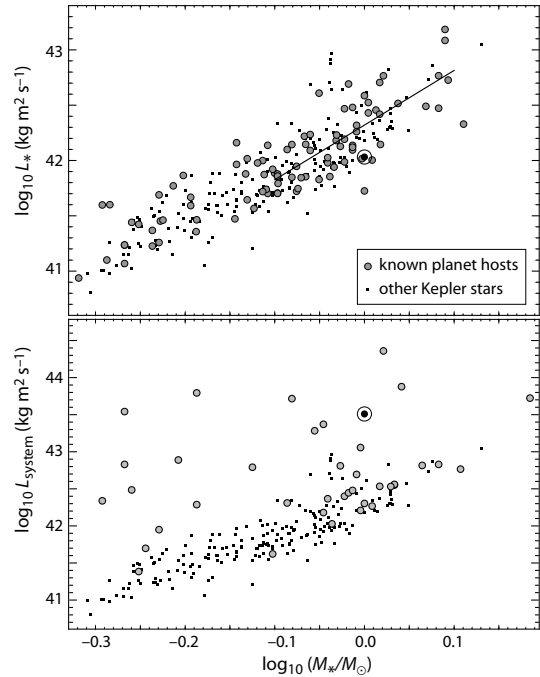


Figure 8.7: Angular momentum versus  $M_*$  for Kepler stars: (a) stellar angular momentum for 131 confirmed Kepler planet hosts (grey circles) and 193 KOIs (black squares). The solid line is the best-fit Kraft relation (Equation 8.13), with  $\alpha = 4.9$ ; (b) total star–planet angular momentum for 38 Kepler planet hosts (grey circles), along with the stellar angular momentum of the same KOI sample (black squares). From Paz-Chinchón et al. (2015, Figure 7a,b), by permission of IOP Publishing/AAS.

angular momentum, with 99% accounted for by the four giant planets (Mestel, 1965a,b).

The ‘problem’ is that models of the Sun’s collapse predict that it would have been spinning rapidly during its earliest epochs, and should dominate the solar system’s angular momentum. It can be explained (e.g. Ray, 2012; Tarakanov & Artamonov, 2015) if the solar wind carried away much of the Sun’s initial angular momentum, with high-velocity escaping particles, entrained in the magnetic field lines, acting as a brake. An alternative is that the early solar system was more massive, and planet formation less efficient, with escaping matter removing significant angular momentum as it formed.

**Application to other systems** With the availability of numerous stellar rotation periods and planetary orbits, an examination of the angular momentum states of other planetary systems can now be made.

A star’s angular momentum can be estimated by assuming it to be a solid and uniform density sphere (e.g. Alves et al., 2010, eqn 1)

$$L_* = \frac{\nu \sin i}{R_*} I_* , \quad (8.11)$$

where  $I_* = (2/5)MR^2$  is the solid body moment of iner-

tia for a sphere,  $v \sin i$  is the projected stellar rotational velocity, and  $R_\star$  is the stellar radius.

The total angular momentum of a planetary system combines the angular momentum of the host star with the orbital angular momentum of its planets (Paz-Chinchón et al., 2015, eqn 1)

$$L_{\text{system}} = \mu \sqrt{G(M_\star + \Sigma M_p) a (1 - e^2)}, \quad (8.12)$$

where  $\mu$  is the reduced mass, and  $\Sigma M_p$  is the total mass of all planets.

For 147 stars both with radial velocity-detected planets, and a control sample without, Alves et al. (2010) demonstrated that the stellar angular momentum follows the *Kraft relation* (Kraft, 1967; Kawaler, 1987)

$$L_\star \propto (M_\star / M_\odot)^\alpha. \quad (8.13)$$

When considering the system's total angular momentum, by including the planet contributions, stars without detected planets showed a clear trend in angular momentum 'deficit' (§10.9.2): for  $M_\star \geq 1.25 M_\odot$  stars without planets tend to have a lower mean angular momentum than planet-hosting stars (their Figure 7).

**Kepler studies** Paz-Chinchón et al. (2015) considered 3807 Kepler stars, determined rotation periods (in the range 2–28 d) for 540, and confirmed the Kraft relation with  $\alpha = 4.9 \pm 1.4$  (Figure 8.7a). Of 131 confirmed planet host stars in this sample, parameters for the computation of the total angular momentum of the star–planet system were available for 38 (Figure 8.7b).

Although most of the planet-hosting Kepler stars exhibit excess stellar angular momentum as compared with the Sun (Figure 8.7a), the angular momentum of the star–planet systems exhibits a somewhat different behaviour: a number of exoplanet host stars exhibit total angular momenta that are comparable to that of the solar system, and others exhibiting a deficit in total angular momentum compared with the Sun (Figure 8.7b).

In a study without corroboration, Zoghbi (2011) has suggested that planetary angular momentum and orbital periods are 'quantised' in integer or half-integer multiples of the stellar rotation.

**Undiscovered planets** Differences in the form of the angular momentum deficit for the Kepler-detected host star sample of Paz-Chinchón et al. (2015), and the radial velocity detected host stars of Alves et al. (2010), may suggest that the Kepler planetary systems host, as yet, undetected planets in much wider orbits.

### 8.3.5 Magnetic fields

Associated with stellar rotation, the role of stellar magnetic fields in the evolution of stellar and planetary systems is known to be important, but is generally poorly constrained by observations. Stellar magnetic braking,

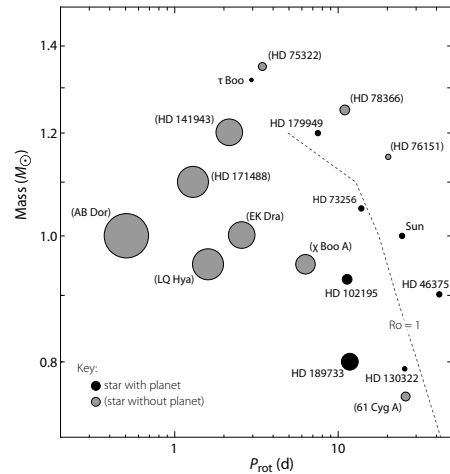


Figure 8.8: Mass–rotation diagram for 18 stars with (black) and without (grey) hot Jupiters. The symbol size is proportional to the stellar magnetic field strength. The dashed line represents Rossby number  $Ro = 1.0$  (with small  $Ro$  linked to rapid rotation). In the original figure, symbols are colour-coded to signify the strength and axisymmetry of the poloidal component. From Fares et al. (2013, Figure 6), © Oxford University Press.

planet migration, and dynamical evolution may be acting simultaneously in the early stages of evolution of the systems, with an impact on the final state that depends on the system properties (Dobbs-Dixon et al., 2004; Lai et al., 2011; Fares et al., 2013).

For short-period planets, star–planet interactions continue throughout the system's lifetime, as the planet may be embedded in the magnetosphere of the star at only a few stellar radii from the stellar surface (§8.10.2). The impact of the stellar wind may then be important (Vidotto et al., 2012), with possible reconnections occurring between the stellar and planetary magnetic fields (Cohen et al., 2010, 2011a; Lanza, 2012). This would influence the planetary magnetic field, the planetary upper atmosphere, and possibly the planet's internal structure. Searches for such effects have been reported, for example, for AB Dor (Jardine et al., 2002), HD 189733 (Fares et al., 2010), and HD 179949 (Fares et al., 2012).

For the star itself, the close-in planet, especially if massive, may induce stellar surface anomalies through magnetic interactions (Shkolnik et al., 2003, 2005; Walker et al., 2008; Pagano et al., 2009; Kopp et al., 2011; Trammell et al., 2011), although several observational searches for such signatures give results that are either unconfirmed, intermittent or difficult to interpret (e.g. Shkolnik et al., 2008; Fares et al., 2012)).

Fares et al. (2013) investigated the large-scale magnetic properties of ten planet-host stars using spectropolarimetry ( $R = 65\,000$  over 370–1000 nm), including the short-cycle star  $\tau$  Boo (cf. §8.10.2). They concluded that stars with and without giant planets tend to have similar magnetic field topologies (Figure 8.8).

## 8.4 Element abundances

Chemical abundance analysis, using high-resolution high signal-to-noise spectroscopy, provides a fundamental diagnostic of host star properties, and an important probe of planet formation and evolution.

### 8.4.1 Metallicity

An important aspect of a star's chemical composition is the fraction of *metals* (in astronomy usage, this term is used to embrace all elements heavier than He). Iron abundance, expressed as  $[\text{Fe}/\text{H}]$ , is frequently used as the reference element for exoplanet host star studies (e.g. Fuhrmann et al., 1997, 1998; Gonzalez, 1997, 1998; Gonzalez et al., 1999; Gonzalez & Laws, 2000; Giménez, 2000; Murray et al., 2001; Santos et al., 2001a; Murray & Chaboyer, 2002; Laws et al., 2003; Santos et al., 2003a, 2004c, 2005, and others).

The abundances of other elements are providing increasingly valuable diagnostics (e.g. Gonzalez, 1998; Gonzalez & Vanture, 1998; Gonzalez & Laws, 2000; Santos et al., 2000a; Gonzalez et al., 2001b; Smith et al., 2001; Sadakane et al., 2002; Zhao et al., 2002; Bodaghee et al., 2003; Ecuivillon et al., 2004a,b, and others).

Already from the earliest studies of just four systems (51 Peg, 55 Cnc,  $\nu$  And, and  $\tau$  Boo) it appeared that stars hosting planets have significantly higher metal content than the average solar-type star in the solar neighbourhood (Gonzalez, 1997). While the Sun and other nearby solar-type dwarfs have  $[\text{Fe}/\text{H}] \sim 0$  (Reid, 2002), typical exoplanet host stars have  $[\text{Fe}/\text{H}] \geq 0.15$ . Values of  $[\text{Fe}/\text{H}] = +0.45$  for two early discoveries, 55 Cnc and 14 Her, placed them amongst the most metal-rich stars in the solar neighbourhood (Gonzalez & Laws, 2000).

Although planets around even very low-metallicity stars have since been found, an overall correlation between metallicity and planet occurrence has been confirmed by subsequent work, using different samples and different analysis procedures.

**Measurement of stellar metallicity** Consistent agreement in determining  $T_{\text{eff}}$  and  $[\text{Fe}/\text{H}]$  has proven notoriously difficult. Results for a given star frequently disagree, as a combined result of differing spectral resolution, the choice of spectral lines, analysis procedures, and the adopted scales of metallicity and  $T_{\text{eff}}$ . For the case of  $\nu$  And (Figure 8.6), for example, nine publications pre-2000 give values spanning the range  $[\text{Fe}/\text{H}] = -0.23$ ,  $T_{\text{eff}} = 6000$  K (Hearnshaw, 1974) to  $[\text{Fe}/\text{H}] = +0.17$ ,  $T_{\text{eff}} = 6250$  K (Gonzalez, 1997). Reasons for difficulties in establishing reliable C/O ratios have also been noted (e.g. Fortney, 2012; Nissen, 2013; Teske et al., 2014).

To establish statistical differences between stars with and without planets at the level of 0.1–0.2 dex, a secure sample of comparison stars is required. The comparison sample should be demonstrably companion-free, and

Table 8.1: An incomplete list of some of the larger compilations of  $[\text{Fe}/\text{H}]$  relevant to exoplanet investigations, mostly for FGK dwarfs. The compilations often provide other parameters such as  $\log g$  and  $T_{\text{eff}}$ .  $N_{\star}$  is the total sample size,  $N_{\text{p}}$  is the number of planet stars hosts when quoted. References are for the latest descriptions in the case of progressively enlarged samples.

$N_{\star}$	$N_{\text{p}}$	Reference
3356	–	Cayrel de Strobel et al. (2001)
14 000	–	Nordström et al. (2004b)
1040	99	Valenti & Fischer (2005)
160	27	Takeda & Honda (2005)
100 000	–	Ammons et al. (2006)
216	55	Luck & Heiter (2006)
1907	–	Robinson et al. (2007a)
118	28	Bond et al. (2008)
451	–	Sousa et al. (2008)

analyses for both samples should preferably be based on the same sets of spectroscopic lines, observed and analysed in the same way. A number of such spectroscopic host star samples and comparison sets have been constructed and investigated.

Santos et al. (2001a) presented a spectroscopic study of a volume-defined set of 43 F8–M1 stars within 50 pc included in the CORALIE programme, and for which constant radial velocities over a long time interval provided evidence that the comparison stars are planet-free. A further 54 comparison stars were added by Santos et al. (2005), yielding two large and uniform samples of 119 planet-host stars, and 94 stars without known planets, all of which have accurate stellar parameters and  $[\text{Fe}/\text{H}]$  estimates. These samples have been the basis of various subsequent abundance analyses (Santos et al., 2003a; Bodaghee et al., 2003; Santos et al., 2004c; Israelian et al., 2004; Gilli et al., 2006). A further 64 comparison stars were added by Sousa et al. (2006).

Other large uniform spectroscopic surveys of exoplanet host stars and comparison stars include (see also Table 8.1): the 99 planet host stars from the 1040 FGK dwarfs of the Keck, Lick, and AAT programme, selected according to magnitude, colour, and luminosity (Valenti & Fischer, 2005); the 27 planet host star and 133 comparison stars observed at Okayama (Takeda et al., 2005; Takeda & Honda, 2005); the 28 planet host stars and 90 comparison stars from the Anglo–Australian planet search programme (Bond et al., 2006, 2008); and the 216 star sample of the ‘nearby stars project’ (Heiter & Luck, 2003; Luck & Heiter, 2005, 2006); 1227 stars in various CoRoT fields using VLT–FLAMES spectroscopy (Gazzano et al., 2010); HST–WFC3 photometry of low-extinction Galactic bulge windows including the SWEEPS (Brown et al., 2010b); a sample of giant and sub-giant stars (Ghezzi et al., 2010a); stars hosting Jovian- and Neptunian-mass planets (Ghezzi et al., 2010c); a sample of metal-poor stars (Sousa et al., 2011a); 52 G-type stars from BOAO (Kang et al., 2011); 76 planet hosts and a control sample of 80 metal-rich stars with-



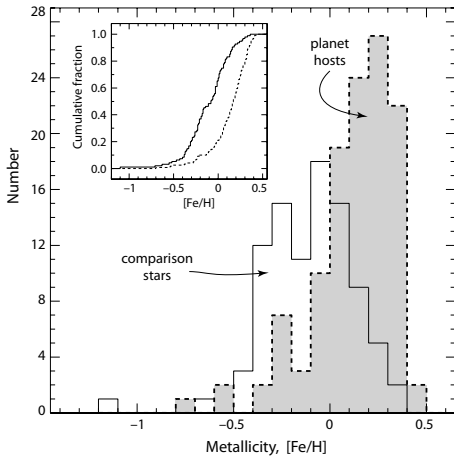


Figure 8.9: Metallicity distribution for 119 planet-host stars (shown as the dashed line, shaded), and for a volume-limited comparison sample of 94 stars with no known planets (continuous line, unshaded). The average metallicity difference of the two samples is 0.24 dex. Inset: cumulative distribution functions. A statistical Kolmogorov–Smirnov test shows that the probability that both distributions belong to the same population is  $\sim 10^{-12}$ . From Santos et al. (2005, Figure 1), reproduced with permission © ESO.

out planets from McDonald Observatory (Brugamyer et al., 2011); 1111 FGK dwarfs from the HARPS programme (Adibekyan et al., 2012c); stars with known debris disks (Maldonado et al., 2012); 61 F/G stars from HARPS (González Hernández et al., 2013); and a sample of 71 evolved stars (Mortier et al., 2013b).

Luck & Heiter (2006) detail the overlap between these and other samples, including the extensive Geneva–Copenhagen spectroscopic and kinematic survey (Nordström et al., 2004a,b).

**The metallicity index [Ref]** Use of the abundance of iron, [Fe/H], to quantify metallicity is widespread in stellar physics, including as a proxy for planet formation. But studies of planet occurrence as a function of stellar type and population have revealed various dependencies, since suspected as being a consequence of this simplistic quantification of metal content.

For these reasons, Gonzalez (2009) introduced the ‘refractory’ index, [Ref] (or [Ref/H]), employing the same spectroscopic notation. It accounts for the fact that Fe is not the only abundant refractory element in the solar system and other planetary systems; Mg and Si have comparable number abundances and condensation temperatures (e.g. Lodders, 2010). Examination of all the elements that go into building giant planets might therefore be more robustly served by considering the mass sum of these three elements

$$[\text{Ref}] = \log(24 \times 10^{(7.55 + [\text{Mg}/\text{H}])} + 28 \times 10^{(7.53 + [\text{Si}/\text{H}])} + 56 \times 10^{(7.47 + [\text{Fe}/\text{H}])}) - 9.538. \quad (8.14)$$

#### Spectroscopic notation:

- $[x/\text{H}] \equiv \log_{10}(N_x/N_{\text{H}}) - \log_{10}(N_x/N_{\text{H}})_{\odot}$ , where  $N_x$  is the number of atoms of element  $x$  per unit volume; thus
- $[\text{Fe}/\text{H}] \equiv \log$  number abundance of Fe/H relative to solar
- $[\alpha/\text{Fe}] \equiv \log_{10}(N_{\alpha}/N_{\text{Fe}}) - \log_{10}(N_{\alpha}/N_{\text{Fe}})_{\odot}$ , the  $\alpha$ -element abundance relative to solar
- ‘metals’: in astronomical usage, generally taken to embrace all elements heavier than He
- dex: a contraction of ‘decimal exponent’, with  $n$  dex meaning  $10^{-n}$ , and 1 dex corresponding to a factor 10

Gonzalez (2009) showed that the use of [Ref/H] in place of [Fe/H] eliminates the apparent preference of giant planets for thick disk stars relative to thin disk stars for  $[\text{Fe}/\text{H}] \leq -0.20$  noted by Haywood (2008) and, hence, any special dependence on Galactic location, as invoked by Haywood (2009). This was subsequently confirmed by Adibekyan et al. (2012c).

The [Ref/H] index also addresses biases in the dependence of planet occurrence as a function of metallicity more generally (Gonzalez, 2014b, see also §8.4.2).

#### 8.4.2 Occurrence versus metallicity

A comparison based on the host star and control samples of Santos et al. (2005) confirmed early indications that the frequency of giant planets rises as a function of [Fe/H] (Figure 8.9).

Similar results were found by Fischer & Valenti (2005), who gave the incidence of Doppler-detected giant planets as  $< 3\%$  for  $[\text{Fe}/\text{H}] < -0.5$ , and  $25\%$  for  $[\text{Fe}/\text{H}] > +0.5$ . Over the range  $-0.5 < [\text{Fe}/\text{H}] < 0.5$ , and for FGK-type main-sequence stars, they expressed the probability of formation of a gas giant planet, with orbital period shorter than 4 yr and  $K > 30 \text{ m s}^{-1}$ , as

$$P(\text{planet}) = \alpha 10^{\beta[\text{Fe}/\text{H}]} = 0.03 \times 10^{2.0[\text{Fe}/\text{H}]} \quad (8.15)$$

From 1266 stars from the California planet survey, Johnson et al. (2010a) suggested a slightly weaker dependency over the range  $0.2 - 1.9 M_{\odot}$  ( $\beta = 1.2$ ), that giant planets continue to become rarer at sub-solar metallicities  $[\text{Fe}/\text{H}] < 0$ , and that planet occurrence increases with  $M_{\star}$  at solar metallicity, with a rise from 3% around M dwarfs ( $0.5 M_{\odot}$ ) to 14% around A stars ( $2 M_{\odot}$ ).

Accounting for various biases (§8.4.2), Gonzalez (2014b) derived a slightly higher  $\beta = 3.0 \pm 0.5$ .

Santos et al. (2017b) used data for all giant planets to show that for  $M_p > 4 M_J$ , host stars tend to be more metal-poor and more massive, with [Fe/H] distributions statistically similar to field stars of similar mass. Stars that host lower-mass planets show the well-established metallicity–giant planet frequency correlation.

As discussed further below, the correlation between occurrence and metallicity may not extend to giant stars (e.g. Maldonado et al., 2013), to stars of intermediate metallicity, to M dwarfs, or to the occurrence of lower-mass planets (Mann et al., 2013b).

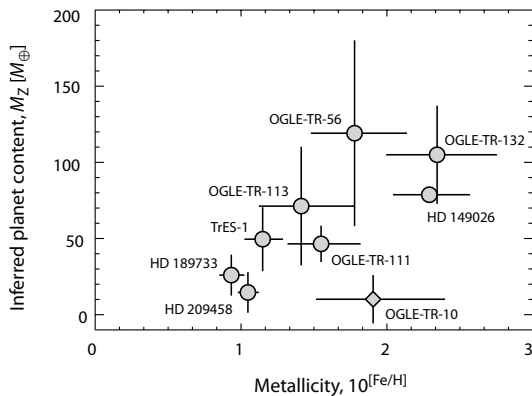


Figure 8.10: Mass of heavy elements in transiting planets as a function of host star metallicity. The mass of heavy elements is that required to fit the observed radii, calculated on the basis of evolution models including an additional heat source assumed equal to 0.5% of the incoming stellar heat flux. From Guillot et al. (2006, Figure 3), reproduced with permission © ESO.

**Transiting planets** The correlation between metallicity and occurrence appears to extend to the close-in giant planets discovered by transit photometry.

To explain the observed radius anomalies for transiting planets known at the time (including HD 209458 and OGLE-TR-10 considered to be anomalously large, and HD 149026 considered to be anomalously small), Guillot et al. (2006) suggested an exoplanet composition/evolution model which included an additional internal energy source equal to 0.5% of the incoming stellar luminosity. This additional heat source acts to slow the cooling of the planet.

With this adjustment, they showed that for the nine transiting planets known at the time, the amount of heavy elements that had to be added to match their observed radii was a steep function of the host star metallicity: from less than  $20M_{\oplus}$  of heavy elements around stars of solar composition, to up to  $100M_{\oplus}$  for stars with three times the solar metallicity (Figure 8.10).

Using evolution models to infer the amount of heavy elements in a sample of 14 transiting planets with only modest stellar insolation, Miller & Fortney (2011) found a correlation between the stellar metallicity and the mass of heavy elements in its transiting planet(s). All giant planets possessed a minimum of  $10\text{--}15M_{\oplus}$  masses of heavy elements, with planets around metal-rich stars having larger heavy-element masses. These results add to the picture that heavy elements play a key role in the formation of close-in giant planets.

A uniform determination of spectroscopic parameters for 13 host stars of transiting planets was made by Ammler-von Eiff et al. (2009), and supplemented by a compilation of results for a total of 50 transit host stars. A systematic offset in the abundance scale was found for the TrES and HAT objects.

**Kepler stars** The large number of planets detected with Kepler has prompted spectroscopic follow-up of many of the Kepler stars, including the determination of fundamental stellar parameters (including  $T_{\text{eff}}$ ,  $M_{\star}$ ,  $R_{\star}$ ) as an input to transit light curve modeling, and an examination of the planet-metallicity dependencies in the Kepler field (e.g. Mann et al., 2012; Muirhead et al., 2012a; Adibekyan et al., 2012a; Bruntt et al., 2012; Everett et al., 2013; Mann et al., 2013b; Creevey et al., 2013; Farmer et al., 2013; Dong et al., 2014b; Rodrigues et al., 2014; Fleming et al., 2015; Niemczura et al., 2015; Schuler et al., 2015; Petigura et al., 2018b).

The LAMOST-Kepler project, one of the largest, targets high-quality, low-resolution spectra with the LAMOST telescope, with more than 100 000 spectra of more than 80 000 objects in the Kepler field acquired to date (De Cat et al., 2015; Gray et al., 2016; Ren et al., 2016). Improved fundamental stellar properties have propagated through to improved planet eccentricities through use of the photo-eccentric effect (Xie et al., 2016, §6.13.11).

Caution in the use of metallicities in the Kepler Input Catalogue (KIC) was advised by Brown et al. (2011b), a conclusion supported by the early 12 000 star sample of the LAMOST survey (Dong et al., 2014b), which found  $[\text{Fe}/\text{H}]_{\text{KIC}} = -0.20 + 0.43[\text{Fe}/\text{H}]_{\text{LAMOST}}$ , with a scatter of  $\sim 0.25$  dex, due almost entirely to errors in KIC.

The California-Kepler Survey targets high-resolution optical spectra with Keck-HIRES (Petigura et al., 2017a). The primary sample is magnitude-limited ( $K_p < 14.2$ ) and contains 960 stars with 1385 planets, extended to include some fainter stars hosting multiple planets, ultra-short period planets, or habitable zone planets. It yields a precision of 60 K in  $T_{\text{eff}}$ , 0.10 dex in  $\log g$ , 0.04 dex in  $[\text{Fe}/\text{H}]$ , and  $1.0 \text{ km s}^{-1}$  in  $v \sin i$ .

Analysis by Petigura et al. (2018b) shows that (transiting) planet occurrence correlates with metallicity for some, but not all, planet sizes and orbital periods. For warm super-Earths with  $P = 10\text{--}100$  d and  $R_p = 1.0\text{--}1.7R_{\oplus}$ , planet occurrence is nearly constant at 20% over metallicities from  $-0.4$  to  $+0.4$  dex. In contrast, the occurrence of warm sub-Neptunes ( $R_p = 1.7\text{--}4.0R_{\oplus}$ ) doubles over the same metallicity interval, from 20% to 40%. Modeling the distribution of planets as  $df \propto 10^{\beta M} dM$ , where  $\beta$  characterises the strength of any metallicity correlation, the correlation steepens with decreasing orbital period and increasing planet size. For warm super-Earths  $\beta = -0.3^{+0.2}_{-0.2}$ , while for hot Jupiters  $\beta = +3.4^{+0.9}_{-0.8}$ . Their interpretation is that high metallicities in protoplanetary disks may increase the mass of the largest rocky cores, or the speed at which they are assembled, enhancing the production of planets larger than  $1.7R_{\oplus}$ . The association between high metallicity and short-period planets may reflect disk density profiles that facilitate the inward migration of solids or higher rates of planet-planet scattering.

**Giant stars** Pasquini et al. (2007) found that planet occurrence around a sample of 14 giant stars does not correlate with increasing metallicity, in contrast with main sequence stars. While they favoured an explanation based on the accretion of metal-rich material (§8.4.3), other interpretations are also possible, perhaps due to differences in migration, or to the presence of a dual-formation mechanism (Matsuo et al., 2007) with a metal-independent mechanism more effective for large stellar masses. The choice of metallicity scale may also be a contributing factor (Santos et al., 2009). A similar trend was found for 322 late-G giants, including 10 planet host stars, by Takeda et al. (2008b).

From their 12-yr Doppler monitoring of 373 G and K giants at Lick ( $M_{\star} = 1 \sim 3.5 - 5.0 M_{\odot}$ ), Reffert et al. (2013) identified 15 planets and 20 candidate planets. They confirmed a strong planet-metallicity correlation, consistent with that for main-sequence stars, and a strong dependence of giant planet occurrence on stellar mass: stars of  $\sim 1.9 M_{\odot}$  have the highest probability of hosting a giant planet, dropping rapidly for  $M_{\star} \geq 2.5 - 3.0 M_{\odot}$ . They found no planets accompanying 113 stars of  $2.7 - 5.0 M_{\odot}$ , concluding that higher mass stars do not form giant planets which are observable at separations of a few au today. Possible reasons include slower growth due to the more distant snow-line, longer migration time scale, and faster disk depletion.

**Stars of intermediate metallicity** Haywood (2008) used  $\alpha$ -element abundances, and the Galactic velocity components (notably the component  $V$  in the direction of Galactic rotation), to classify the fourteen exoplanet host stars in the metallicity range  $-0.7$  to  $-0.2$  dex according to their membership of the thin disk or thick disk populations. All but one belong to the thick disk, and just one to the metal-poor tail of the thin disk. A similar result for older, lower metallicity host stars with enhanced  $[\alpha/\text{Fe}]$  had been noted by Reid et al. (2007).

The classification by population is possible because, at these intermediate metallicities, stars in the solar vicinity fall into two main groups: the thin disk being solar in  $\alpha$ -elements and rotating faster than the *local standard of rest* (viz. the velocity of a hypothetical group of stars in strictly circular orbits at the solar position), while the thick disk is enriched in  $\alpha$ -elements,  $[\alpha/\text{Fe}] > 0.1$  dex, and lags the local standard of rest.

The distinct properties of the thin and thick disk in terms of  $\alpha$ -element enrichment as a function of metallicity are illustrated in the studies of e.g. Fuhrmann (1998), and Reddy et al. (2003, 2006).

**M dwarfs** The complex spectra of low-mass M dwarfs precludes the use of standard LTE spectroscopic modeling, and the knowledge of their metallicity distribution has been based until recently on photometric calibration (Bonfils et al., 2005a). This calibration originally suggested that M dwarfs in the solar neighbourhood,

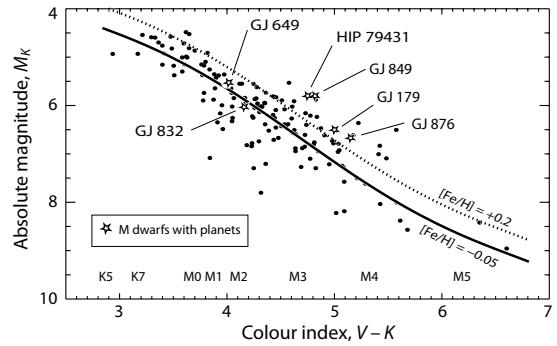


Figure 8.11: Nearby low-mass stars from the Keck sample in the  $M_K$  versus  $V - K_s$  plane, with the corresponding spectral types shown at bottom. Small black circles indicate a volume-limited sample of single K dwarfs ( $d < 20$  pc) and M dwarfs ( $d < 10$  pc). The solid line is a fifth-order polynomial fit to the mean main sequence, and corresponds to roughly solar metallicity. Open symbols indicate all M dwarfs known to harbour at least one giant planet. From Johnson et al. (2010d, Figure 1), reproduced by permission, Institute of Physics Publishing.

including those with known planets, are systematically metal poor compared to their higher-mass counterparts (Bean et al., 2006).

Johnson & Apps (2009) derived a revised metallicity calibration based on  $V - K_s$  photometry of a volume-limited sample with common proper motion companions and found that, in contrast, M dwarfs with planets appear to be systematically metal rich. The mean metallicity for their M dwarf sample with planets is  $\text{Fe}/\text{H} = +0.16$ , compared with  $+0.15$  for the FGK dwarfs with planets. The result brings the M dwarfs into a consistent pattern of metallicity excess being correlated with planet occurrence. There is still a systematically lower fraction of Jovian planets around M dwarfs than FGK dwarfs at any given metallicity, a result likely to be a reflection of their lower stellar masses, rather than an effect of metallicity.

By late 2010, seven Doppler-detected giant planets were known around six M dwarfs (Figure 8.11). From their volume-limited Keck sample, Johnson et al. (2010d) estimate that  $3.4^{+2.2}_{-0.9}\%$  of stars with  $M_{\star} < 0.6 M_{\odot}$  host planets with  $M \sin i > 0.3 M_J$  and  $a < 2.5$  au. Restricted to metal-rich stars with  $[\text{Fe}/\text{H}] > +0.2$ , the occurrence rate rises to  $10.7^{+5.9}_{-4.2}\%$ .

**Neptune-mass planets** The first Doppler detections of low-mass planets suggested that their occurrence might show a different dependence on the host star metallicity than for giant planets (e.g. Udry et al., 2006).

Sousa et al. (2008) derived  $[\text{Fe}/\text{H}]$  for 451 stars from HARPS. They found that, in contrast to the giant Jupiter-mass planets, Neptune-like planets do not form preferentially around metal-rich stars, with the ratio of Jupiter to Neptune mass planets being an increasing function of metallicity.

**Metallicity and orbital period** A weak correlation between metallicity and orbital period was reported by Sozzetti (2004). In several later studies with larger samples, no such correlation was evident (Fischer & Valenti, 2005; Jones et al., 2008b), nor indeed with eccentricity or planet mass (Bond et al., 2008).

For a large FGK dwarf planet-host star sample, Adibekyan et al. (2013b) showed that planets orbiting metal-poor stars have longer periods than those in metal-rich systems, a trend valid over planet masses  $10M_{\oplus}$  to  $4M_J$ , including the hot Jupiter population. Various effects could be responsible. Observations might be simply biased in favour of planets around metal-rich stars (Santos et al., 2005). It could arise from the efficiency of the planet formation processes, with planets in metal-poor disks preferentially forming farther from their central star. Disk-driven migration might be dependent on the metallicity of the host star and its disk, especially for type I migration which depends on the disk opacity (e.g. Mordasini et al., 2009b).

Alternatively, as shown by Bolmont et al. (2017a), tidal evolution of close-in massive planets may depend on metallicity through the tidal dissipation properties of the convective envelope of the rotating star. On the pre-main sequence, they found that the dissipation of metal-poor solar-type stars is higher than that of a metal-rich Sun-like star, a situation reversed on the main sequence. The dependence of dissipation on metallicity is much less evident for stars of  $0.4M_{\odot}$ . Their orbital evolution model qualitatively reproduces the observational trends of the hot Jupiter population with host star metallicity.

Pinotti et al. (2005) proposed a model in which the semi-major axis of its most massive planet, prior to migration, and accordingly reflecting some optimal orbit of giant planet formation, correlates host star metallicity, which they termed the *zero age planetary orbit* hypothesis (ZAPO). Confirmed in a sample a factor 10 larger by Pinotti et al. (2017), their hypothesis predicts that planets around metal-poor stars are formed nearer to their host star. As a consequence, they would be more frequently engulfed by their host star during migration, or stripped of their gaseous envelopes.

Further out, the formation of debris-generating planetesimals at tens of au may be independent of the metallicity of the primordial disk (Greaves et al., 2006).

**Metallicity–occurrence biases** That the occurrence trend versus metallicity might arise from various observational biases has been considered in some detail, although none of the effects identified seems likely to invalidate the basic correlation.

Most radial velocity surveys are biased against very young stars with their high rotational velocities or high chromospheric activities, effects quantified by Paulson & Yelda (2006). They are also biased against multiple star systems and metal-poor stars, although the latter are only poorly represented in the solar neighbourhood. Magnitude-limited and volume-limited surveys result in different representations of stars of different spectral types (Fischer & Valenti, 2005). Even the distance-limited criterion of Santos et al. (2005) is not a volume-limited survey, since their sample of F8–M1 stars within 50 pc does not include all late G, K, and M dwarfs.

A more subtle bias against low-mass high-metallicity stars results from a magnitude cut-off, while a colour cut-off gives the opposite (Murray & Chaboyer, 2002).

Radial velocity surveys preferentially detect planets with short orbital periods and large masses. An observed metallicity correlation could therefore reflect a dependence of orbital radius on metallicity, perhaps suggesting a dependence of migration rate on metallicity (Gonzalez, 2003; Sozzetti, 2004; Gonzalez, 2006a).

Gonzalez (2014b) described three corrections that should be applied: (a) diffusion in the stellar atmosphere, and its effects on the inferred *bulk* metallicity, (b) use of the [Ref/H] index in place of the [Fe/H] index, better suited to relating the stellar composition to giant planet formation, and (c) correction for the space velocity ( $W$ ) selection bias, in which volume-limited surveys necessarily undersample stars that spend most of their time far from the Galactic mid-plane. Applying these gave a slightly *enhanced* dependency of planet occurrence as a function of [Fe/H] (§8.4.2).

### 8.4.3 Origin of the metallicity difference

Excluding the possibility of selection bias, two principal hypotheses have been put forward to explain the connection between high metallicity and the presence of massive planets: either causative as a consequence of higher primordial abundances facilitating accretion, or by self-enrichment as a result of the capture of metallicity-enhanced material. Based on the additional evidence described below, the current consensus is that while some host stars may be polluted to some degree by material capture, and while other effects are likely to complicate the picture, the dominant effect is likely to be primordial, with planets simply more likely to form around metal-rich stars.

**Primordial occurrence** According to this (prevailing) hypothesis, the high metallicity observed in certain hosts is a bulk property of the star, and represents the original composition out of which the protostellar and protoplanetary molecular clouds formed.

In this picture, the higher the metallicity of the primordial cloud, the higher the dust/gas ratio in the protoplanetary disk. This facilitates condensation, and accelerates protoplanetary accretion, before the gas disk is lost (Pollack et al., 1996). Giant planets are subsequently formed by runaway accretion of gas onto such rocky cores of mass  $\sim 10M_{\oplus}$ , rather than by gravitational instabilities in a gaseous disk which predicts formation much less sensitive to metallicity (Boss, 2002). The cut-off in the metallicity distribution for host stars at  $[\text{Fe}/\text{H}] \geq 0.5$  (Figure 8.9) then represents the upper limit to metallicities in the solar neighbourhood.

Observationally, the probability of forming a giant planet appears to be proportional roughly to the square of the number of Fe atoms (Equation 8.15). Since particle collision rates are similarly proportional to the square of the number of particles, this result has been further used to argue a physical link between dust particle collisions in the primordial disk and the formation rate of giant planets. Based on the core accretion model, Kornet et al. (2005), Wyatt et al. (2007a), and Ida & Lin (2004b, 2005a) were able to reproduce the distribution of giant planets with host star metallicity. The latter model also predicts that short-period giant planets should be rare around M dwarfs, but that Neptune mass ice-giant

planets might be common, a trend which is broadly apparent in M dwarf Doppler surveys (Endl et al., 2006a).

If metallicity determines the time scale for giant planet formation, there should be a correlation between planet mass and metallicity. Rice & Armitage (2005) showed some evidence for this correlation, although the same trend is not evident in the studies of, e.g., Bond et al. (2008, their Figure 4).

**Self-enrichment** An alternative explanation is that the high metallicity is restricted to the surface region of the star, arising from the capture of metal-rich material, and the resulting ‘pollution’ of its outer convective envelope. This might be the result of the terminal inward migration of a planet onto the star due to dynamical friction (Laughlin & Adams, 1997; Gonzalez, 1998; Siess & Livio, 1999b; Israelian et al., 2001; Sandquist et al., 2002; Israelian et al., 2003), self-pollution due to the transfer of gas-depleted, metal-rich material from disk to star as a result of migration (Goldreich & Tremaine, 1980; Lin et al., 1996; Laughlin, 2000; Gonzalez et al., 2001b), or to the break-up and infall of planets or planetesimals onto the star due to gravitational interactions with other companions (Rasio & Ford, 1996; Queloz et al., 2000b; Quillen & Holman, 2000; Quillen, 2002).

A planet added to a fully convective star would be folded into the entire stellar mass, and would lead to a negligible overall metallicity enhancement. However, main sequence solar mass stars like the Sun have radiative cores with relatively small outer convection zones comprising only a few percent of the stellar mass. At ages of  $\geq 10^8$  yr the Sun’s outer convection zone had reduced to  $\sim 0.03M_{\odot}$  (Ford et al., 1999, and Figure 8.12). For higher mass stars, the convection zone is smaller still ( $0.006M_{\odot}$  at  $1.2M_{\odot}$ ), so that the sensitivity of surface metallicity to accreted matter rises steeply for stars more massive than the Sun.

Under these conditions, planet capture could significantly enhance the heavy element content in the convective zone, resulting in elemental abundances deviating from the underlying trends resulting from Galactic chemical evolution (Figure 8.12). Planet hosts having the shallowest convection zones would be expected to have the highest metallicities (Laughlin & Adams, 1997; Ford et al., 1999; Siess & Livio, 1999b; Pinsonneault et al., 2001; Li et al., 2008b). Other aspects of surface enrichment are detailed under Li abundance (§8.4.7) and white dwarf photospheres (§8.9).

**Implications of self-enrichment** Studies have pursued various implications of the self-enrichment model. Murray & Chaboyer (2002) estimated that some  $5M_{\oplus}$  of iron would have to be slowly accreted over some 50 Myr to explain the observed mass–metallicity and age–metallicity relations. Sandquist et al. (1998) showed that a capture event may also influence the further orbital migration of other planets in the system due

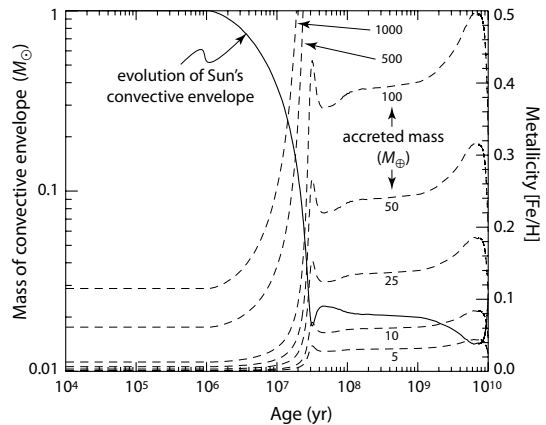


Figure 8.12: High metallicity arising from pollution. The solid line (left axis) shows the evolution of the Sun’s convective envelope. Dashed lines (right axis) indicate the surface metallicity that would result from the instantaneous accretion of rocky material onto the star at each time in the Sun’s past (masses in  $M_{\oplus}$ ), assuming that the accreted material is mixed throughout the convective envelope. Producing high surface metallicities of 0.2–0.3 dex is possible with the accretion of  $\sim 10 - 25M_{\oplus}$  of rocky material after  $10^7$  yr. From Ford et al. (1999, Figure 5), by permission of IOP Publishing/AAS.

to changes in angular momentum or magnetic field. Sandquist et al. (2002) argued that the core of a cold infalling giant planet could penetrate the convection zone. Cody & Sasselov (2005) developed a stellar evolution code to model stars with non-uniform metallicity distributions, motivated by the phenomenon.

One test of the enrichment hypothesis makes use of the fact that when a star leaves the main sequence, its convection zone deepens significantly. This would lead to strong dilution if the high metallicity is a result of surface pollution. Fischer & Valenti (2005) used their sample of 1040 nearby FGK dwarfs (Valenti & Fischer, 2005), including 99 planet hosts, to show that there is no correlation between host metallicity and the convection zone depth, either while the star is on the main sequence, or after it evolves to the subgiant branch and its convection zone deepens (Figure 8.13). This result has been taken to support the primordial basis of the correlation.

Another test of self-enrichment is to search for compositional differences between common proper motion pairs (i.e. binary components with large separations), which presumably formed together out of the same molecular cloud with the same chemical composition. Accretion has been invoked to explain abundance anomalies in the binary 16 Cyg A and 16 Cyg B (where the planet orbits the B component), which have very different Fe abundances and Li content (Gonzalez, 1998; Laws & Gonzalez, 2001). Similar arguments were given for HD 219542 (Gratton et al., 2001), although the exoplanet host status of the latter was subsequently retracted (Desidera et al., 2003). Various other proper

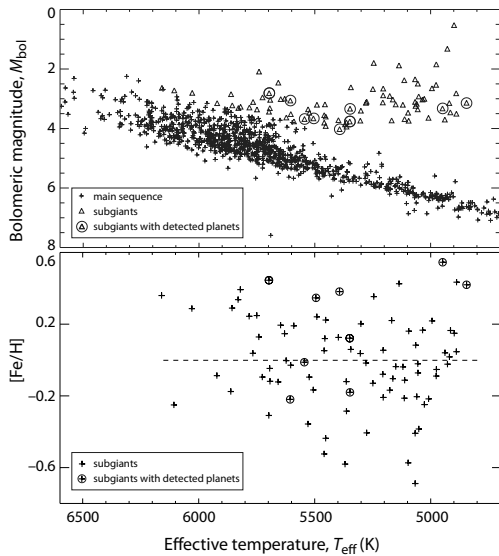


Figure 8.13: Top: Hertzsprung–Russell diagram for stars from the Keck, Lick, and AAT planet search projects, as of 2005. Symbols distinguish main sequence stars, subgiants ( $M_{\text{bol}} > 1.5$  mag above the lower main sequence), and subgiants with detected planets. Bottom: subgiants, with detected planets circled. If high metallicity correlated with the presence of Jovian planets is limited to the convective envelope of main sequence stars, subgiants with planets should show progressively lower metallicity due to dilution as they evolve across the subgiant branch. No such gradient is observed. From Fischer & Valenti (2005, Figures 11–12), by permission of IOP Publishing/AAS.

motion pairs have been studied (Desidera et al., 2004b, 2006; Luck & Heiter, 2006), although the implications for the reported differences remain unclear.

Other evidence for accretion has been attributed to the presence of  ${}^6\text{Li}$  (§8.4.7), in the metal-rich dwarf HD 82943 (Israeli et al., 2001, 2003), in 59 Vir (Fuhrmann, 2004), in non-planet hosting stars including the super-lithium-rich F dwarf J37 in NGC 6633 (Laws & Gonzalez, 2003; Ashwell et al., 2005), and for various white dwarfs (Jura, 2006).

**Solar enrichment** Notwithstanding a general consensus that the occurrence–metallicity correlation is essentially primordial, material accretion would appear to be an inevitable by-product of planet formation and evolution. The Sun, for example, continues to accrete cometary material today: accretion of up to  $100M_{\oplus}$  of metal-rich material was proposed as a partial resolution of the solar neutrino problem (Jeffery et al., 1997), although such a mass is probably ruled out by helioseismic models (Winnick et al., 2002). Nevertheless, the differences between solar photospheric and meteoritic abundances display a weak but significant trend with condensation temperature, suggesting that the metallicity of the Sun’s envelope has been enriched relative to its interior by  $\sim 0.07$  dex (Gonzalez, 2006b).

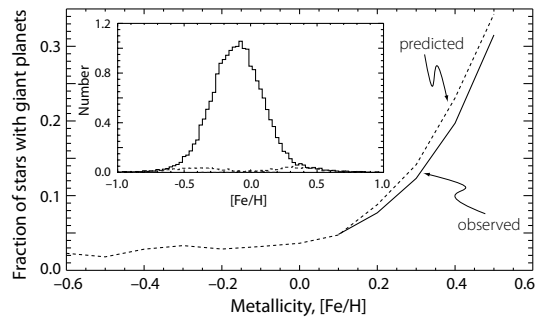


Figure 8.14: Inset: the simulated ‘local’ metallicity distribution (main histogram). The contributions of the metal-rich and metal-poor components assumed to have come to the solar neighbourhood by radial migration are shown by the lower dashed line. Main: the predicted fraction of stars with giant planets obtained assuming the metallicity distribution and intrinsic giant planet proportion of 0% in the metal-poor component, 5% locally, and 25% in the metal rich component (dashed line). The solid line is the fraction of planet hosts versus stellar metallicity according to Udry & Santos (2007). From Haywood (2009, Figure 4b), by permission of IOP Publishing/AAS.

**Thermohaline convection** The process of *thermohaline convection* complicates the above picture. According to this, high-metallicity material added to the star during planet engulfment does not remain in the surface layers, but diffuses into the interior. Also referred to as ‘fingering’ convection, it is named after the oceanographic process in which warm salt water, originally above cooler layers of lower salinity, rapidly moves downwards, despite a stabilising thermal gradient, due to ‘double diffusion’ between the descending ‘fingers’ and their surroundings.

A similar process is inferred to operate in stars with an inverted gradient of mean molecular weight, even in a thermally-stabilised medium (Ulrich, 1972; Vauclair, 2004, 2008; Traxler et al., 2011; Garaud, 2011; Théado & Vauclair, 2012; Deal et al., 2013a). The stages in this process are described in more detail by Garaud (2011, Section 5). This instability is likely to occur whenever heavy elements accumulate in the outer layers of a star. Garaud (2011) estimated the rate at which added heavy elements diffuse into the stellar interior, finding that high relative metallicity enhancement post-infall drops by a factor 10 over a time scale that decreases very rapidly with increasing stellar mass, from about 1 Gyr at  $1.3M_{\odot}$  to 10 Myr at  $1.5M_{\odot}$ .

The process may explain the lack of an observed correlation between metallicity and convection zone mass in planet host stars, and may provide further evidence that the higher metallicity of planet-bearing stars must be primordial. Given that the ‘fingering region’ extends deep into the star, and in particular down to the Li-burning region, it may also explain the higher Li depletion rates in planet-bearing stars (§8.4.7).

**Different Galactic origins** As noted above, initial studies suggested that the correlation between metallicity and the occurrence of giant planets appears to break down for giant stars, and for intermediate metallicity stars for which giant planets were reported as preferentially orbiting thick disk stars (Haywood, 2008). Haywood (2009) then suggested that the occurrence–metallicity correlation is a dynamical manifestation of stellar migration in the Galactic disk. Giant planet for-

**Thin and thick disk populations:** While dominated by thin disk stars, the local stellar population contains some 5–10% of thick disk stars, and some 0.1–0.5% of halo stars. Studies of nearby stars are therefore closely connected with the determination and segregation of the ages, chemical composition, and velocity structures of the various component populations. Significant sub-structure in the local disk is also present in the form of open clusters, moving groups, and associations, including the Gould Belt.

The recognition of the existence of stellar populations differing in age, chemical composition, spatial distribution, and kinematic properties, represented a breakthrough in the knowledge of Galactic structure, and underpins the basis for recent models of galaxy formation and evolution. An extensive literature now exists on the topic of the Galaxy's disk: its separation into thin and thick disk components, whether they represent discrete or continuous populations, their respective scale heights, their kinematic, metallicity, and age properties, and their origin.

The vertical distribution of the different populations is frequently described either in terms of a *characteristic thickness*, defined as the ratio of the surface density (integrated over disk thickness) to its volume density at the Galactic plane, or in terms of a *scale height*,  $z_h$ , defined by  $\exp(-z/z_h)$  for an exponential distribution. The thin and thick disks have characteristic thicknesses of 180–200 pc and 700–1000 pc respectively, with the interstellar medium having a scale height of about 40 pc (Dehnen & Binney, 1998). Even for the thin disk, however, its scale height is different for different classes of stars, with old stars found at greater distances from the plane partly as a result of disk heating in which the irregular gravitational field of spiral arms and molecular clouds gradually increases their random velocities over time.

Galactic rotation and velocity dispersions are of order  $\langle V_{\text{rot}} \rangle = 205, 180 \pm 50, 20$  and  $\sigma_{uvw} = 20, 50, 100$  for the thin, thick and halo components respectively (Reid, 1998), where the components  $uvw$  are taken conventionally towards the Galactic centre, in the direction of Galactic rotation, and towards the north Galactic pole, respectively. Numerous determinations can be found in the literature (e.g. Soubiran et al., 2003; Bensby et al., 2004).

mation was then hypothesised to correlate with Galactocentric distance, rather than being primarily linked to metallicity, according to the following picture.

**Detailed models** Most metal-rich stars ( $\text{Fe}/\text{H} > +0.25$  dex) found in the solar neighbourhood, including those hosting planets, are considered to have migrated from the inner disk, i.e. from within the solar Galactocentric radius, by the effect of radial mixing (Sellwood & Binney, 2002; Adibekyan et al., 2014). Given a Galactic radial metallicity gradient of  $0.07\text{--}0.1$  dex  $\text{kpc}^{-1}$  (e.g. Edvardsson et al. 1993; Wielen et al. 1996 and references; Maciel & Costa 2009), stars with a mean metallicity  $[\text{Fe}/\text{H}] = +0.35$  will have originated at about 3–5 kpc from the Sun in the direction of the Galactic centre. If 25% of stars at this location systematically host giant planets, independent of metallicity, then the observed correlation between occurrence and metallicity follows from dilution due to radial mixing.

The origin of the Sun is not inconsistent with this picture. Wielen et al. (1996) inferred its birthplace at a Galactocentric radius of  $R_{i,\odot} = 6.6 \pm 0.9$  kpc, based on its metallicity which is

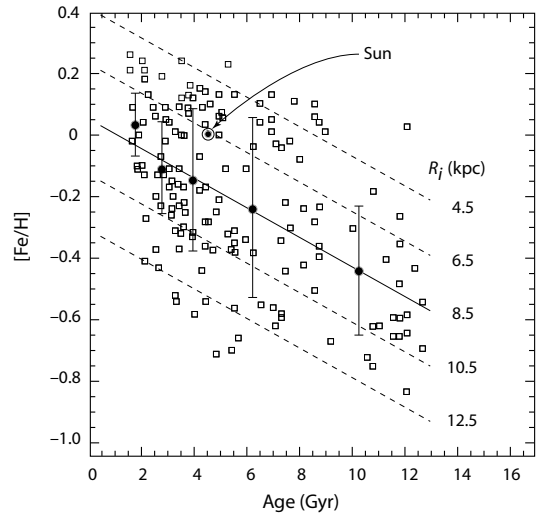


Figure 8.15: Places of formation of stars which are now nearby. Metallicity  $[\text{Fe}/\text{H}]$  is plotted against age for stars from the sample of Edvardsson et al. (1993). The Sun's position is indicated. Inclined lines are of constant Galactocentric distance for their age–metallicity relation, such that the place of formation,  $R_i$ , can be determined for each star, including the Sun. Mean metallicities versus age are shown as filled circles. From Wielen et al. (1996, Figure 3), reproduced with permission © ESO.

larger by  $0.17 \pm 0.04$  dex than the average of nearby stars of solar age, combined with a similar radial Galactic metallicity gradient. This is also consistent with its space motion (Figure 8.15).

Haywood (2009) suggested that planet formation is related, not to metallicity, but to the presence of molecular hydrogen in the form of the Galaxy's molecular ring (Clemens et al., 1988; Jackson et al., 2006). This provides a large reservoir of  $\text{H}_2$ , itself considered to be directly linked to star formation (e.g. Kennicutt, 2008). At its maximum density of 2–5 times its local density, 3–5 kpc from the Sun, planets are then expected to form preferentially. In this picture, the region of enhanced giant planet formation 'happens' to correspond to the metallicity range of 0.3–0.5 dex. Combined with radial mixing, this model offers consistency with the proportion of giant planets found around metal-rich and solar-metallicity stars (Figure 8.14).

In this picture, the giant star giant-planet hosts contain only a limited bias towards metal-rich objects because they are typically younger than the dwarfs, with ages of  $< 1$  Gyr (Takeda et al., 2008b). Their relative youth implies that they are less contaminated in metallicity by radial mixing. The hypothesis would have a further observational consequence: stars hosting non-giant planets, i.e. of Neptune or Earth mass, may form in less dense  $\text{H}_2$  environments, such that a predominance of metal-rich stars among the Neptune/super-Earth hosts is not expected. Such behaviour has been confirmed in the HARPS results noted previously (Sousa et al., 2008).

As noted in Section 8.4.1, Gonzalez (2009) showed that the use of a more general 'refractory' abundance measure,  $[\text{Ref}/\text{H}]$ , in place of  $[\text{Fe}/\text{H}]$ , eliminates the apparent preference of giant planets for thick disk stars relative to thin disk stars for  $[\text{Fe}/\text{H}] \leq -0.20$  noted by Haywood (2008) and, hence, any special dependence on Galactic location, as invoked by Haywood (2009). This was subsequently confirmed by Adibekyan et al. (2012c).

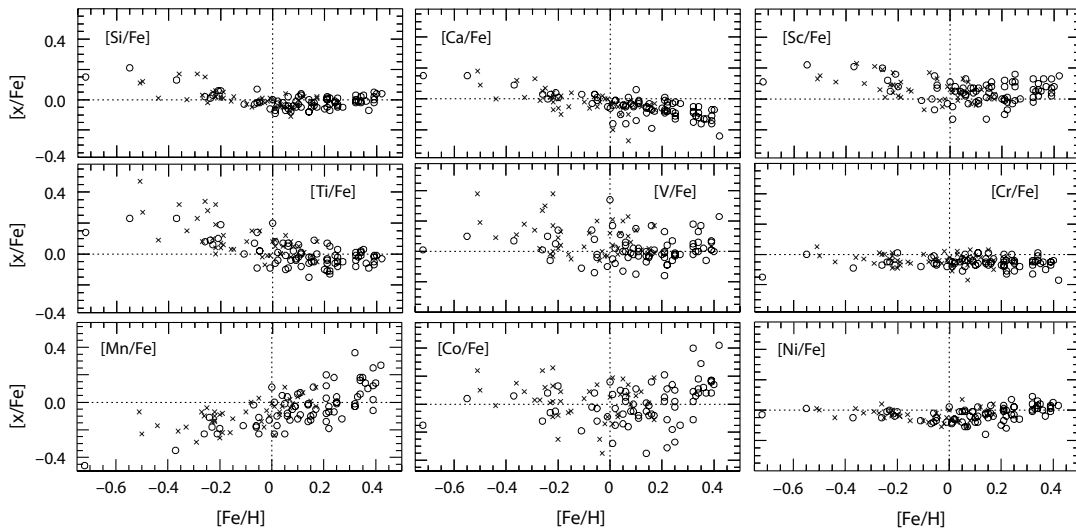


Figure 8.16:  $[x/Fe]$  versus  $[Fe/H]$  for nine (moderately) refractory elements. Open circles denote the planet-host stars, and crosses represent comparison stars. Dashed lines represent values for the Sun. From Bodaghee et al. (2003, Figure 2), reproduced with permission © ESO.

#### 8.4.4 Refractory and volatile elements

Planet formation involves *condensation*, the change from gaseous phase into the liquid or solid phase of the same element or chemical species. This involves the loss of kinetic energy by collision, or by adsorption onto an existing, colder, condensation centre.

In planetary science, elements and compounds with high equilibrium condensation temperatures are referred to as *refractory*, while those with low condensation temperatures are referred to as *volatile*.<sup>1</sup>

Of the elements most studied in the context of planet host stars, the (moderately) refractory include Al, Ca, Ti, and V; those with intermediate condensation temperatures include Co, Fe, Mg, Ni, and Si; while the (moderately) volatile include C, Cu, N, Na, O, S, and Zn.

If the correlation between occurrence and metallicity originates from primordial abundances, then simi-

lar occurrence trends may be expected for metals other than iron. Self-enrichment should, in contrast, result in overabundance of refractory elements in the stellar photosphere, and a reduced abundance of volatile elements due to preferential evaporation (Smith et al., 2001).

**Refractory elements** For metals in general, values of  $[x/H]$  typically show enhancements for stars with planets, as in the case of  $[Fe/H]$ . Studies of the relative abundances of refractory or moderately refractory elements have conveyed a less clear-cut picture when comparing values of  $[x/Fe]$  for planet hosts to those of comparison stars of the same  $[Fe/H]$ .

Takeda et al. (2001) and Beirão et al. (2005) reported no significant trends in the various elements which they studied. Gonzalez et al. (2001b) found smaller values of Mg and Al (as well as Na), with no significant differences for Si, Ca, and Ti, but with less significant differences found in later studies (Gonzalez, 2006b). Sadakane et al. (2002) reported some host stars with the volatile elements C and O underabundant with respect to the refractories Si and Ti. Huang et al. (2005) reported a possible Mg enhancement.

A comparison for 77 planet hosts and 42 comparison stars was made by Bodaghee et al. (2003), with results for Si, Ca, Sc, Ti, V, Cr, Mn, Co and Ni shown in Figure 8.16. Their conclusion is that the abundance trends of the refractory elements,  $[x/Fe]$  versus  $[Fe/H]$ , for planet hosts are largely identical to those for the comparison stars at the corresponding (high) values of  $[Fe/H]$ . The work was extended to 101 stars with and 93 without known planetary companions by Gilli et al. (2006).

<sup>1</sup>More details can be found in, e.g., Larimer (1988); Cowley (1995); Taylor (2001), and the topic is considered further in §11.2.2. Briefly, the demarcation is set by the condensation temperature of the ‘common elements’ Mg, Si, and Fe, while condensation temperatures are themselves (weakly) pressure dependent. Further sub-classification, is somewhat arbitrary and defined variously. For example, Taylor (2001) uses very volatile (condensation temperatures < 700 K), volatile (700–1100 K), moderately volatile (1100–1300 K), moderately refractory (1300–1500 K), refractory (1500–1700 K), and super-refractory (> 1700 K). A slightly different classification is suggested by Lodders (2003), who uses: highly volatile (< 371 K), volatile (371–704 K), moderately volatile (704–1290 K), intermediate (1290–1360 K), refractory (1360–1500 K), highly refractory (1500–1650 K), and ultra-refractory (> 1650 K).



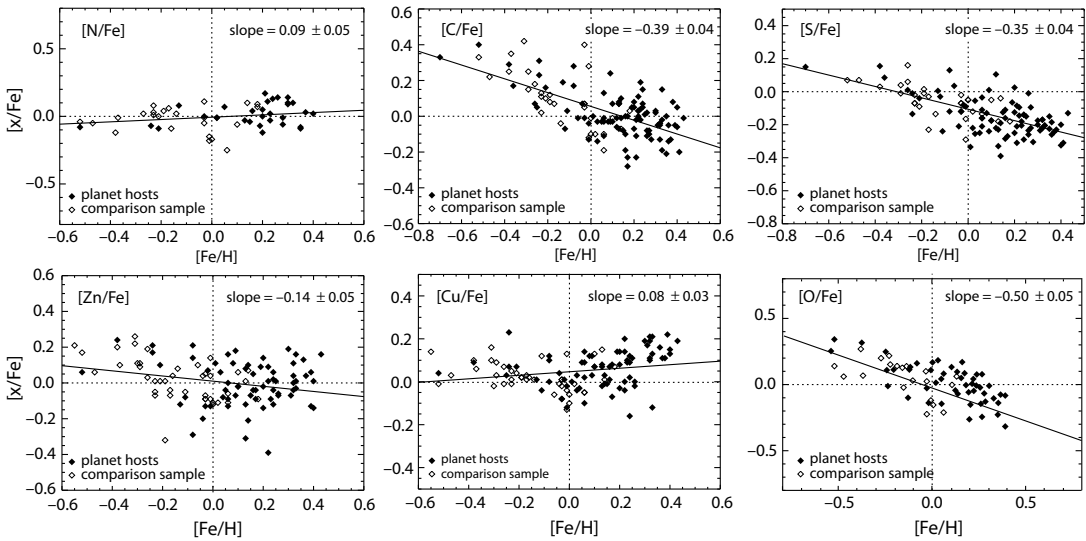


Figure 8.17:  $[x/\text{Fe}]$  versus  $[\text{Fe}/\text{H}]$  for the (moderately) volatile elements N, C, S, Zn, Cu, O. Planet host stars are shown as filled diamonds, and comparison stars as open symbols. Linear least-squares slopes apply to all objects. From Ecuivillon et al. (2004b, Figure 7b) for N; Ecuivillon et al. (2004a, Figures 8–11) for C, S, Zn, Cu; and Ecuivillon et al. (2006b, Figure 10e) for O, reproduced with permission © ESO.

Some evidence for Si and Ni enrichment of planet host stars compared with the general metal-rich population was reported by Robinson et al. (2006a) using the 1040 FGK dwarf sample of Valenti & Fischer (2005), but these results were not confirmed by Gonzalez & Laws (2007). The latter studied 18 elements in 31 host stars, finding some differences between their comparison sample in the case of Al, Si, and Ti, but also demonstrating some inconsistencies with previous results. Brugamy et al. (2011) found a planet-detection dependency on Si, although not for O, hinting that grain nucleation, rather than subsequent icy mantle growth, is the important limiting factor in forming giant planets via core accretion. Carter-Bond et al. (2012a) examined the Mg/Si dependencies. Adibekyan et al. (2012c) found a modest overabundance in giant planet host stars for 12 refractory elements in a sample of 1111 FGK stars with 109 exoplanet hosts from the HARPS planet search programme. For the same sample, abundances of Cu, Zn, Sr, Y, Zr, Ba, Ce, Nd, and Eu, and their various dependencies on stellar population, are given by Delgado Mena et al. (2017). Abundances of Fe, O, C, Mg, and Si for a large sample of solar neighbourhood stars from different populations suggests that, assuming that the overall chemical composition planets reflects that of the host star, rocky planets can be formed with significantly different Fe/Si mass fractions, and very different  $\text{H}_2\text{O}$ -content, dependent on Galactic population (Santos et al., 2017a; Unterborn & Panero, 2017).

Adibekyan et al. (2014) focused on a sample of 148 solar-like stars to search for a possible correlation be-

tween the slopes of the abundance trends versus condensation temperature,  $T_c$ , with stellar parameters and Galactic orbital parameters. They found that the  $T_c$  slope correlates with stellar age, stellar surface gravity, and possibly with the mean Galactocentric distance, suggesting that stars that originated in the inner Galaxy have fewer refractory elements relative to the volatiles, and that the age and probably the Galactic birth place influence the star's chemical properties.

Notwithstanding some small and possibly important abundance differences, the broad conclusion is that planet-hosting stars are largely indistinguishable, or at least with rather modest overabundances, from other Population I stars in their enrichment histories of refractory elements. One implication of this result is that no extraordinary chemical events, such as a nearby supernova, are necessary to stimulate planet formation.

**Volatile elements** C and O are significant opacity sources in stars, and important in the chemistry of protoplanetary disks. Their forbidden lines are preferentially used as abundance indicators, but they are weak and blended, and demand high-quality spectroscopy.

Both Gonzalez & Laws (2000) and Santos et al. (2000a) reported sub-solar values for  $[\text{C}/\text{Fe}]$  and  $[\text{Na}/\text{Fe}]$  in planet host stars, while subsequent investigations using inhomogeneous comparison samples gave a more uncertain picture of the trends for  $[\text{C}/\text{Fe}]$ ,  $[\text{O}/\text{Fe}]$ , and  $[\text{N}/\text{Fe}]$  (Gonzalez et al., 2001b; Takeda et al., 2001; Sadakane et al., 2002; Takeda & Honda, 2005).

The uniform sample of planet hosts and comparison

stars defined by Santos et al. (2001a) was used in a series of studies (Ecuivillon et al., 2004a,b, 2006a,b) to derive abundances of N, C, S, Zn, Cu and O (Figure 8.17). While most elements show a decreasing trend of  $[x/Fe]$  with increasing  $[Fe/H]$ , the overall conclusion is again that the abundance trends for planet host stars for the (moderately) volatile elements,  $[x/Fe]$  versus  $[Fe/H]$ , are largely identical to those for the comparison stars at the corresponding (high) values of  $[Fe/H]$ . Some evidence for S enhancement was reported by Huang et al. (2005). No significant trends in various elements were found by Gonzalez (2006b), nor for C in the 172 star sample of G/K stars by da Silva et al. (2011).

With no compelling evidence of preferential volatile depletion amongst stars with planets, most investigators have concluded that the metal enrichment of planet hosts is primordial, and that stars hosting giant planets form preferentially in metal-rich molecular clouds.

**Implications for terrestrial planet formation** Gonzalez et al. (2001a) estimated that a metallicity at least half that of the Sun is required to build a habitable terrestrial planet, as dictated by heat loss, volatile element inventory, and atmospheric loss. The concentrations (with respect to Fe) of the radiogenic isotopes  $^{40}K$ ,  $^{235}U$ ,  $^{238}U$  and  $^{232}Th$  will affect the efficiency of plate tectonics (Urey, 1955), which may be an important recycling process providing feedback to stabilise temperatures on planets with oceans and atmospheres, while the relative abundances of Si and Mg (with respect to Fe) affect the mass of the core relative to the mantle.

Since all these elements and isotopes vary with time and location within the Galaxy as a result of star formation activity, even planetary systems with the same metallicity as the Sun will not necessarily form habitable Earth-like planets. Regions of the Galaxy accordingly least likely to contain Earth-mass planets are the halo, the thick disk, and the outer thin disk. The bulge should contain Earth-mass planets, but with a different mix of elements compared to the Sun.

If stellar abundances reflect planetary abundances, spectroscopic host star studies may also represent a step in identifying terrestrial planet composition and evolution. Stars with different Mg/Si ratios may have terrestrial planets with differing compositions of the pyroxene-silicate mineral series  $(Mg,Fe)SiO_3$ , or of the olivine series  $(Mg,Fe)_2SiO_4$ , compositions likely to affect volcanic activity and plate tectonics.

Lineweaver (2001) assumed that the probability of forming Earths is proportional to metallicity. With very low metallicity, Earths are unable to form, but with a very high metallicity, giant planets would dominate and destroy planets of terrestrial mass. The resulting probability for a stellar system to harbour an Earth-like planet is shown in Figure 8.18. Combined with estimates of the star formation rate, and the gradual build-up of met-

**The r-process, s-process, and  $\alpha$  elements:** The elements are considered to have been broadly formed as follows (Burbidge et al., 1957; Thielemann, 2002): H in the Big Bang; He in the Big Bang (and in stars); C and O in low- and high-mass stars; Ne-Fe ( $Z = 10 - 26$ ) in high-mass stars; Co-Bi ( $Z = 27 - 84$ ) in the s- and r-processes; and Po-U ( $Z = 84 - 92$ ) in the r-process. The s- and r-processes (for slow and rapid neutron capture, with respect to the  $\beta$ -decay rate of the nuclei, respectively) are the two principal paths leading to the 'trans-Fe' elements.

The *s-process* involves neutrons liberated during core and shell He-burning being captured by a nucleus, with the neutron subsequently undergoing  $\beta$ -decay to produce a proton. It being easier to add the chargeless neutron to a nucleus than it is to add a proton directly, this results in the progressive build-up of elements up to Pb and Bi, starting on existing heavy nuclei around Fe. It is thought to occur mostly in asymptotic giant branch stars during the thermal pulse stage (e.g. Reddy et al., 2003).

The *r-process* involves the rapid addition of many neutrons to existing nuclei, which again decay into protons, producing the heavier elements. The r-process is a subset of explosive Si-burning, which differs strongly from its hydrostatic counterpart, and is thought to occur only in supernovae, and mostly in those of Type II, the end points of massive star evolution, rather than those of Type Ia, resulting from binary systems (Qian, 2003). Observational evidence is based on the existence of elements like Au, and the fact that in some of the oldest stars in the Galaxy, which were formed after only a small number of Type II supernovae had enriched the interstellar medium, the abundance of Fe is very low, while the abundances of r-process elements are anomalously high.

*$\alpha$ -elements* are those whose most abundant isotopes are integral multiples of the He nuclei or  $\alpha$ -particle: (C, N, O), Ne, Mg, Si, S, Ar, Ca, and Ti. Type Ia supernovae predominantly produce elements of the iron peak (V, Cr, Mn, Fe, Co and Ni) as a result of normal freeze-out of charged particle reactions during cooling. Low-density freeze-outs, most pronounced in Type II supernovae, leave a large  $\alpha$  abundance, and a higher proportion of  $\alpha$ -elements. This includes O, so that O enhancement is well correlated with the presence of  $\alpha$ -elements. C and N, as well as O, are sometimes included within the class since they are synthesized by nuclear  $\alpha$ -capture reactions, although the enrichment of the interstellar medium by C and N is not due to Type II supernova explosions but due to stellar winds of the more massive asymptotic giant branch stars.

als, Lineweaver (2001) derived an estimate of the age-distribution of Earth-like planets in the Galaxy, finding that three quarters of Earth-like planets are older than Earth, with an average age  $1.8 \pm 0.9$  billion years older.

**Snow line** Planet formation models involve the concept of a *snow line* (§11.2.3), the distance from the central protostar beyond which it is cool enough for hydrogen compounds such as  $H_2O$ ,  $NH_3$ , and  $CH_4$  to condense into solid ice grains, demarcating the regions in which terrestrial and Jovian planets can form. Depending on density, the temperature of the snow line is estimated to be about 150 K, and it lies at around 2.7 au in

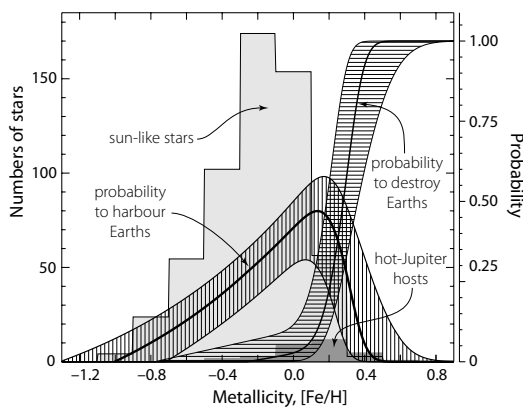


Figure 8.18: For a given metallicity, the probability of destroying Earths is taken to be the ratio of the number of hot Jupiter hosts to the number of stars surveyed. The probability of harbouring Earth-like planets assumes that the production of Earths is linearly proportional to metallicity, but is cut off at high metallicity by the increasing probability to destroy Earths. From Lineweaver (2001, Figure 1), with permission from Elsevier.

the present solar system. Lower temperatures beyond the snow line makes more solid grains available for accretion into planetesimals and eventually into planets.

The short-lived isotope  $^{26}\text{Al}$  ( $\tau_{1/2} \sim 7 \times 10^5$  yr), produced from Ar by cosmic-ray spallation, has long been recognised as a possible heat source responsible for differentiation of early planetesimals (Urey, 1955). Such a phase is invoked to explain thermal processing in some meteorites. Heating by  $^{26}\text{Al}$  may also impose a *snow moment*, with planetesimals forming earlier than this being depleted of volatiles (Gilmour & Middleton, 2009).

**Implications for SETI observers** Something of an aside relates to the possibility of searching for developed civilisations in parallel with host star spectroscopic characterisation. Both Drake (1965) and Shklovskii & Sagan (1966) independently suggested that extraterrestrial civilisations could announce their presence by adding a short-lived isotope into their stellar atmosphere, such that external observers could detect its absorption lines, and recognise its artificial origin.

#### 8.4.5 The r- and s-process elements

The very different origins of the r- and s- process elements means that their abundances provide information on the history of the material incorporated into planets and their host stars, as well as on overall models of Galactic chemical evolution. Various studies of their occurrence in stars without planets have been reported (e.g. Edvardsson et al., 1993; Allende Prieto et al., 2004; Bensby et al., 2005; Reddy et al., 2006).

Studies of these elements are now also being made for exoplanet host stars. Huang et al. (2005) included the s-process Ba in their broader study of abundances of 22 host stars, finding  $[\text{Ba}/\text{Fe}]$  typically solar. Gonzalez & Laws (2007) included the r-process Eu amongst their study of 18 elements in 31 host stars.

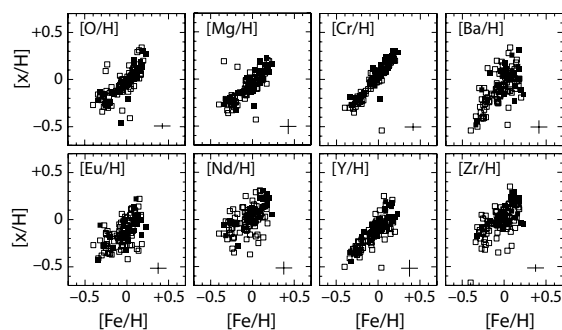


Figure 8.19:  $[x/\text{H}]$  versus  $[\text{Fe}/\text{H}]$  for the planet hosts and comparison stars from the Anglo–Australian planet search programme. Filled squares represent host stars, and open squares represent non-host stars. Typical error bars are shown at the bottom right of each panel. The r- and s-process elements are Ba, Eu, Nd, Y, Zr. From Bond et al. (2008, Figure 1), by permission of IOP Publishing/AAS.

A more extensive study of 28 host stars and 90 comparison stars from the Anglo–Australian planet search programme was reported by Bond et al. (2008). In addition to the elements C, Si, O, Mg, and Cr, they determined abundances for Eu (r-process), Ba, Y, and Zr (s-process), and Nd (arising from both processes). Their results show that the abundances in host stars are different from both the standard solar abundances and the abundances in non-host stars in all elements studied, with enrichments over non-host stars ranging from 0.06 dex for O, to 0.11 dex for Cr and Y (Figure 8.19).

The results provide further evidence that metal enhancement observed in planetary host stars is the result of normal Galactic chemical evolution processes, and that the observed chemical traits of planetary host stars are primordial in origin.

#### 8.4.6 The alpha elements

Israelian (2008) has drawn attention to three unexpected trends which appear in the behaviour of the  $\alpha$  elements, whose abundances primarily reflect their production in Type II supernovae (box, page 398).

The reasonably uniform star formation history over the 10 Gyr history of the Galactic disk, leads to the expectation that the slope of  $[\alpha/\text{Fe}]$  versus  $[\text{Fe}/\text{H}]$  should be rather constant (Tsujiimoto et al., 1995a). In contrast, present evidence suggests that the  $\alpha$  element ratios  $[\text{Si}/\text{Fe}]$ ,  $[\text{Ti}/\text{Fe}]$ , and  $[\text{Mg}/\text{Fe}]$  show a rather abrupt change at  $[\text{Fe}/\text{H}] \sim 0$ , becoming rather flat (Figure 8.16), while  $[\text{Ca}/\text{Fe}]$  decreases with increasing  $[\text{Fe}/\text{H}]$  (Gonzalez et al., 2001b; Sadakane et al., 2002; Bodaghee et al., 2003; Beirão et al., 2005; Gilli et al., 2006).

The abundance ratio  $[\text{O}/\text{Fe}]$  continues to decrease at  $[\text{Fe}/\text{H}] > 0$  (Ecuillon et al., 2006b, and Figure 8.17), without showing the flattening seen in the F–G field dwarf study of Nissen & Edvardsson (1992).

**Origin and depletion of lithium:** Lithium provides an important diagnostic of both primordial nucleosynthesis and of (pre-) main sequence stellar evolution. Essentially,  ${}^7\text{Li}$  is produced in the Big Bang, along with  ${}^2\text{H}$  (deuterium),  ${}^3\text{He}$ , and  ${}^4\text{He}$ . Its primordial abundance therefore provides an important test of Big Bang nucleosynthesis (Burbidge et al., 1957).  ${}^6\text{Li}$  is produced primarily through cosmic-ray fusion reactions with the interstellar gas (e.g., Fields & Olive, 1999).

Both isotopes are destroyed at relatively low temperatures due to their low binding energies:  ${}^6\text{Li}$  at  $T \geq 2 \times 10^6$  K, and  ${}^7\text{Li}$  at  $T \geq 2.5 - 3 \times 10^6$  K, the precise values of  $T$  depending on the time scale of the transport mechanism below the convective zone as a result of the accelerating reaction rates with temperature (Lumer et al., 1990; Montalbán & Rebolo, 2002). At typical main sequence densities,  ${}^7\text{Li}$  survives only in the outer 2–3% of the stellar mass. Otherwise, when surface material is mixed down to depths where  $T \geq 2.5 \times 10^6$  K, Li burning occurs, primarily through the reaction  ${}^7\text{Li}(p, \alpha){}^4\text{He}$  (Caughlan & Fowler, 1988), and Li depleted material is returned to the surface. In giants, surface Li decreases as a consequence of dilution.

Li abundance therefore reflects the mixing of matter, element diffusion, and angular momentum evolution throughout the star's evolutionary history (Pinsonneault et al., 1992; Pinsonneault, 1997; Stephens et al., 1997; Montalbán & Rebolo, 2002), providing a sensitive but complex diagnostic. The *lithium test*, for example, uses the presence or absence of Li to distinguish candidate brown dwarfs from low-mass stars (Rebolo et al., 1992, 1996).

High Li abundance coupled with high chromospheric activity often indicates stellar youth, although alone it is not considered to be a reliable tracer of age for solar-type stars (e.g., Pasquini et al., 1994; Mallik, 1999).

A complication in understanding the distribution of lithium in the Galaxy is the existence of the 'Spite plateau' (Spite & Spite, 1982a,b), the uniform  ${}^7\text{Li}$  abundance in halo dwarfs spanning a wide range of  $T_{\text{eff}}$  and metallicity, but at a factor of ten below the abundances found in young Population I objects (Charbonnel & Primas, 2005).

The behaviour of [C/Fe] and [N/Fe] (Ecuivillon et al., 2004a,b, and Figure 8.17) are qualitatively different, despite the fact that Galactic chemical evolution models predict similar trends for all the  $\alpha$  elements down to [Fe/H] = 0 (Tsujimoto et al., 1995b).

Despite the small number of low-metallicity planet-hosting stars, various studies have shown that they tend to be enhanced by  $\alpha$ -elements (e.g. Haywood, 2008, 2009; Kang et al., 2011; Adibekyan et al., 2012b,a). This enhancement suggests that, in the metal-poor regime, most of the planet-hosting stars belong to the Galactic thick disk, although whether this is linked to the birth place of the stars (Haywood, 2008, 2009, §8.4.3), or to their specific chemical composition (Adibekyan et al., 2012b) has been less clear.

Adibekyan et al. (2012a) found that over  $-0.65 < [\text{Fe}/\text{H}] < -0.3$  dex, the fraction of Ti-enhanced planet-hosts is  $12 \pm 4\%$  for the thick disk, but only  $2 \pm 1\%$  for the thin disk. Adibekyan et al. (2012b) found that

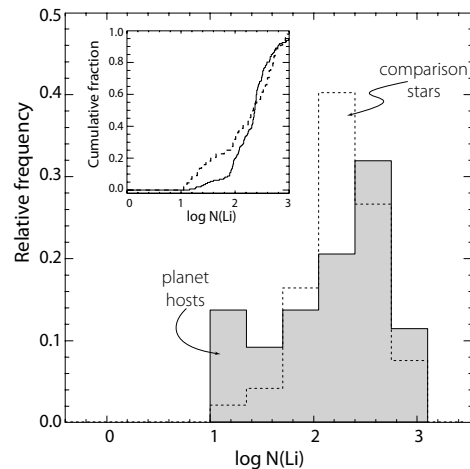


Figure 8.20: Lithium distribution for stars with planets (solid line/shaded). The distribution for comparison stars without planets (dotted line), from Chen et al. (2001), is significantly different. Inset: cumulative distribution functions. From Israelian et al. (2004, Figure 4), reproduced with permission © ESO.

this  $\alpha$ -element anomaly existed also for Mg, Al, Si, and Sc, being largest for Mg. They concluded that metals other than Fe may be important for planet formation at low metallicities and that, with conditions being more favourable in the thick disk, it is the chemical conditions (rather than Galactic birth place) which is the determining factor for the formation of rocky planets.

#### 8.4.7 Lithium

**Context** Lithium has an important diagnostic role in astronomy and cosmology. As a result of its primordial genesis and relative ease of destruction in stars (box, page 400), the degree of Li depletion reflects the turbulent mixing of matter, element diffusion, and angular momentum evolution throughout a star's history; if Li is transported from the surface to deeper and hotter regions by convection or other mixing processes, atmospheric Li abundance will decrease with time.

In solar-type stars, rotation and angular momentum loss are among the leading processes believed to generate the mixing that leads to the general depletion of light elements, both Li and Be (e.g. Stephens et al., 1997; Bouvier, 2008), although mixing by internal gravity waves may also contribute (Montalbán & Schatzman, 2000).

Due to additional mixing processes which might operate on a star-by-star basis, observed Li abundances may provide information on the past accretion history of protoplanetary disk material, planets and planetesimals (Alexander, 1967; Gonzalez, 1998; Montalbán & Rebolo, 2002), and on tidal interactions between the host star and close-orbiting planets due to resulting changes in its rotation rate (Chen & Zhao, 2006; Takeda et al., 2007b).

**Lithium in the Sun** The Sun is assumed to have destroyed most of its Li over its 4.5 Gyr lifetime, since its surface abundance is less than 1% of that in the most pristine meteorites (Anders & Grevesse, 1989). Furthermore, the Sun has a lower Li content than observed in many solar-type stars in the solar neighbourhood. There has been a long-standing debate as to whether the Sun's Li abundance is unusual compared with stars of otherwise similar properties.

Standard models of the Sun's evolution does not predict significant Li destruction, since the convection zone is not thought to extend deep enough for lithium burning to occur. It follows that there must be an additional mixing process at work.

Given the large spread in Li abundance in stars in the solar neighbourhood (by factor of  $> 100$ ), this mixing and corresponding lithium destruction probably depends sensitively on the detailed properties of the star, such as its mass, effective temperature, surface gravity and metallicity.

**Exoplanet observations** Central to various exoplanet investigations has been the suggestion that stars *with* planets tend to have less Li than stars without. If the presence of planets somehow enhances Li destruction in the star, it raises the possibility of identifying stars likely to host planets solely from a determination of their Li content. The low solar abundance would, in such a picture, be a consequence of the Sun having planets.

Only one line, of Li I near 670.8 nm, is available as a diagnostic in solar-type stars. Several stars now known to have planetary systems were recognised as having low Li abundances prior to discovery of their planetary companions, including  $\rho$  CrB (Lambert et al., 1991). The large Li difference between 16 Cyg A and B had also been noted, despite their similar  $T_{\text{eff}}$  (Friel et al., 1993).

Following the confirmation of the first exoplanetary systems, King et al. (1997b) examined 16 Cyg A and B further, and commented on six other systems, but considered that the sample size was too small to draw conclusions. Based on eight planet host stars, Gonzalez & Laws (2000) suggested that stars with planets tend to have smaller Li abundances when corrected for differences in  $T_{\text{eff}}$ , [Fe/H], and chromospheric emission. Ryan (2000b) reached a different conclusion based on 17 stars, after eliminating young chromospherically-active stars and subgiants as being at different evolutionary stages, and therefore with systematically different Li abundances.

From a larger sample of 79 planet hosts, and 157 comparison stars from Chen et al. (2001), Israelian et al. (2004) found a difference in the two distributions (Figure 8.20), with an excess Li depletion in planet host stars in the range  $T_{\text{eff}} = 5600 - 5850$  K, but with no significant differences at higher temperatures (Figure 8.21).

These results were confirmed in an independent study based on 160 F-K disk dwarfs and subgiants, in-

cluding 27 planet-host stars, by Takeda & Kawanomoto (2005), although not by Luck & Heiter (2006). A uniform treatment of Li abundances was compiled by Gonzalez (2008), who assembled data (including upper limits) for 37 planet host stars and 147 comparison stars from previous publications (Israelian et al., 2004; Takeda & Kawanomoto, 2005; Luck & Heiter, 2006; Gonzalez & Laws, 2007; Takeda et al., 2007b). This study confirmed the smaller Li abundances for planet hosts near 5800 K, and presented new evidence that planet hosts around 6100 K have an excess Li.

From 451 stars from the HARPS programme, 70 with planets, Israelian et al. (2009) found that half the solar analogues without detected planets have some 10% of the primordial Li abundance, while the planet bearing subset have less than 1%, with neither age nor metallicity correlated with the excess depletion (Figure 8.22).

While some later studies continued to report an absence of depletion for planet-hosting stars (Ghezzi et al., 2010b; Ramirez et al., 2012; Carlos et al., 2016), the majority have continued to find significant Li depletion in planet-hosting stars (Gonzalez et al., 2010; Delgado Mena et al., 2014; Figueira et al., 2014a; Gonzalez, 2014a, 2015a; Delgado Mena et al., 2015).

At the same time both Delgado Mena et al. (2015) and Gonzalez (2015a) have drawn attention to a number of pairs of stars, one of each pair with a planet and the other without, with very similar properties, yet with very different Li abundances. For a sample of 21 solar twins, Carlos et al. (2016) found no correlation between stars with and without planets, but with the majority showing a strong correlation between Li abundance and stellar age (their Figure 5).

**Evidence for planet engulfment** Infrared excess and high Li abundances are observed in 4–8% of G/K stars. Siess & Livio (1999b) postulated that these originate from the accretion of a giant planet, brown dwarf, or low-mass star. Discovery of  ${}^6\text{Li}$  in the atmosphere of metal-rich solar-type HD 82943, known to have an orbiting giant planet, may be evidence of a planet having been engulfed by the host star (Israelian et al., 2001).

High Li abundance, perhaps attributed to recent planet engulfment, has also been reported in the giants BD+48 740 (Adamów et al., 2012) and HD 233604 (Nowak et al., 2013), for the class of rapidly rotating red giants (Carlberg et al., 2013; Adamów et al., 2014). and in HD 96423 and HD 38277 (Carlos et al., 2016).

Abundance differences in refractory elements (0.2 dex) and surface Li (0.5 dex) in the comoving pair of bright solar-type stars, HD 240429 and HD 240430, separated by 0.6 pc, suggests that HD 240430 accreted  $15M_{\oplus}$  of rocky material after birth (Oh et al., 2018).

**Theoretical considerations** The general trend for stars at the lower temperatures to destroy Li more effectively, as noted by Israelian et al. (2004) and others, is

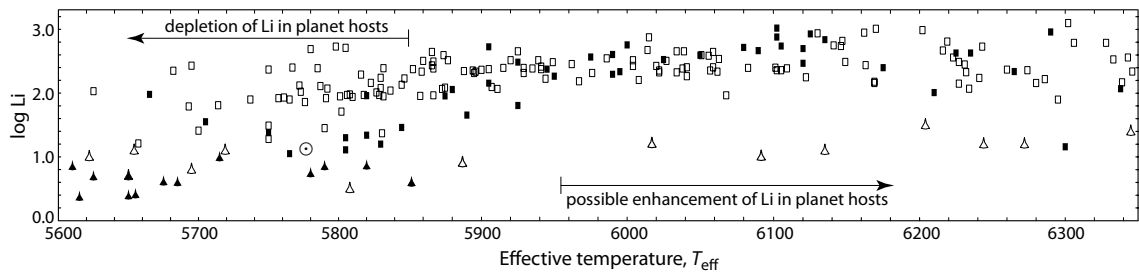


Figure 8.21: Lithium versus effective temperature for stars with planets (filled squares) and the comparison sample of Chen et al. (2001) (empty squares). Upper limits are indicated as filled triangles for planet hosts, and open triangles for the comparison sample.  $\odot$  indicates the position of the Sun. A regime of possible Li enhancement is indicated according to the subsequent results of Gonzalez (2008). From Israelian et al. (2004, Figure 5), reproduced with permission © ESO.

consistent with their deeper convection zones, while for stars more massive than the Sun the convective layers do not extend to Li-burning temperatures, and they therefore preserve a large fraction of their original Li.

But an additional cause of Li depletion in exoplanet host stars is necessary to explain any preferential depletion compared with non-host stars. One possibility (Israelian et al., 2004; Chen & Zhao, 2006; Israelian et al., 2009) is that angular momentum transfer arising from star–disk interactions during the pre-main sequence phase resulted in systematically slower stellar rotation at the beginning of its main sequence evolution.

Some stellar evolution models which include rotation (e.g. Bouvier et al., 1997; Allain, 1998) predict that while fast rotators evolve with little decoupling between core and envelope, slower rotators develop a high degree of differential rotation. This strong differential rotation at the base of the convective envelope may then result in enhanced lithium depletion in the slower rotators (Bouvier, 2008; Castro et al., 2008, 2009). Not all theoretical models concur with this picture: Pinsonneault et al. (1989) found a rotational shear at the base of the convective envelope which scales with surface velocity.

Findings by Gonzalez (2008) that the observed Li abundance anomalies are further correlated with rotation ( $v \sin i$ ), as well as chromospheric activity ( $R'_{\text{HK}}$ ), nevertheless suggest that planet formation processes have indeed altered the rotational history and Li abundances of stars that host Doppler-detected planets.

A corollary of this explanation is that long-lived disks ( $> 5$  Myr) may be a necessary condition for massive planet formation and migration (Bouvier, 2008). Theoretical work may point in the same direction (Goodman & Rafikov, 2001; Sari & Goldreich, 2004), while some relation between disk mass and a star’s rotation history is rather well established (Edwards et al., 1993; Stassun et al., 1999; Barnes et al., 2001; Rebull, 2001; Rebull et al., 2002; Hartmann, 2002; Wolff et al., 2004). Accretion of planetary mass bodies onto a star can also lead to angular momentum spin-up (Siess & Livio, 1999b).

Another process may be associated with the infall of (proto-)planetary material onto the star during various phases of the planetary system’s evolution. Baraffe & Chabrier (2010) studied the effect of episodic accretion on the internal structure of low-mass and solar type stars. They found that it can produce objects with significantly higher central temperatures than their non-accreting counterparts, thus explaining the higher Li depletion in planet-hosting stars. Their model was based on episodes of short, intense bursts of accretion with typical accretion rates of  $10^{-4} - 5 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ , as inferred from 2d hydrodynamical simulations of gravitationally unstable accretion disks (Vorobyov & Basu, 2005), and assuming an instantaneous and uniform redistribution of the extra source of internal energy brought by the accreted material. Sousa et al. (2010) showed that the observed correlations do not originate from differences in stellar mass and age.

**The presence of  ${}^6\text{Li}$**  As a result of the different temperatures at which  ${}^6\text{Li}$  and  ${}^7\text{Li}$  are destroyed, stellar evolution models can predict whether  ${}^6\text{Li}$ ,  ${}^7\text{Li}$ , or both, are consumed at particular stages of their evolution, as a function of mass and metallicity (Montalbán & Rebolo, 2002). Thus standard models (e.g. Forestini, 1994) predict that  ${}^6\text{Li}$  cannot survive pre-main sequence mixing in metal-rich solar-type stars.

Accordingly,  ${}^6\text{Li}$  should not be present in the atmosphere of a normal solar-type star, but could be present in a star that has accreted planetary matter. Its presence could conceivably provide some discrimination between different giant planet formation scenarios (Sandquist et al., 2002).

The presence of  ${}^6\text{Li}$  is manifested as a red asymmetry in the Li I, but its inferred contribution must be decoupled from similar effects due to convective motions (Ghezzi et al., 2009). It has been reported in the planet host star HD 82943 by Israelian et al. (2001), and attributed to the infall of rocky material (see also Sandquist et al., 2002), with the infrared excess reported for the system by Beichman et al. (2005b) perhaps im-

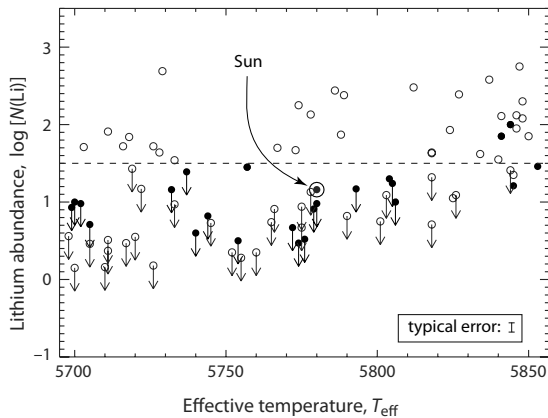


Figure 8.22: Li abundances for planet-hosting (filled circles) and single comparison stars (open circles) from the HARPS study. The dashed line matches the upper envelope of the lower limits corresponding to a minimum  $S/N=200$  in a typical solar twin. The two planet-hosting stars with the highest Li abundance also have nearly the highest  $T_{\text{eff}}$  and therefore thinner convective zones, which help to preserve Li. Other than in these stars,  $\log[N(\text{Li})]=1.5$  is the highest value found in a planet-hosting star. From Israelian et al. (2009, Figure 1), by permission from Nature/Springer/Macmillan Ltd, ©2009.

plying that recent collisions have provided suitable accreting material. The detection was subsequently contested by Reddy et al. (2002), confirmed by Israelian et al. (2003), but further questioned by Ghezzi et al. (2009).

Unsuccessful searches were reported in eight planet-hosting stars by Reddy et al. (2002), in a further two by Mandell et al. (2004), and in five more by Ghezzi et al. (2009). Whatever the nature of HD 82943, these negative results suggest that post-main sequence accretion of planets or planetary material that is undepleted in lithium is not common.

#### 8.4.8 Beryllium

Like lithium, beryllium ( ${}^9\text{Be}$ ) is used as a tracer of the internal structure and (pre-) main sequence evolution of solar-type stars. It has a higher thermonuclear destruction temperature of  $\sim 3.6 \times 10^6$  K (Caughlan & Fowler, 1988; Lumer et al., 1990; Boesgaard et al., 2004).

Early abundance studies, using the  ${}^9\text{BeII}$  doublet at  $\lambda = 313.1065$  nm, were made for 55 Cnc (García Lopez & Pérez de Taoro, 1998) and 16 Cyg A/B (King et al., 1997a; García Lopez & Pérez de Taoro, 1998; Deliyannis et al., 2000). Santos et al. (2002a) reported Be abundances for 29 planet hosts and six single stars, finding several Be-depleted stars at 5200 K.

Studies for a sample of 41 planet hosts and 29 stars without known planets (Santos et al., 2004b,d) suggested that planet hosts have normal Be abundances, again supporting a primordial origin for the metallicity excess of planet host stars. Santos et al. (2004b) also found a few

late-F and early-G dwarf planet-hosts that might have higher than average Be abundances, perhaps related to the engulfment of planetary material, but more likely attributable to Galactic chemical evolution, or to mass differences for stars of similar  $T_{\text{eff}}$ .

An enlarged sample of 100 stars, and new spectroscopy with VLT-UVES, allowed a comparison of the Be content of 70 with planets and 30 without (Gálvez-Ortiz et al., 2011). No significant differences were found. Extending the sample to include 14 cooler stars, Delgado Mena et al. (2011) found just one (HD 330075) showing enhanced Be depletion by 0.25 dex.

From a further enlargement to 89 and 40 stars with and without planets respectively ( $T_{\text{eff}} = 4700 - 6400$  K), Delgado Mena et al. (2012) found a fall-off in Be for  $T_{\text{eff}} < 5500$  K, but independently of the presence of planets. They argued that for  $T_{\text{eff}} < 5500$  K there is a mechanism destroying Be not reflected in current models of Be depletion; and that the suggested phenomenon of additional Li depletion in solar-type stars accompanied by planets does not seem to be present for Be.

### 8.5 Occurrence versus stellar type

Ideally, some empirical *planetary distribution function* would describe the distribution of planet masses, orbits and multiplicities in terms of stellar mass, metallicity, and other properties such as age, spin rate, multiplicity and Galactic location. It would then characterise all properties of the exoplanet population (such as the fraction of stars in the Galaxy with planetary systems, or the frequency of planets of a given mass in the solar neighbourhood), and would provide constraints on detailed population synthesis models (§10.13.2).

The various discovery methods indeed now span a wide range of planetary masses and orbital parameters over a broad range of host star properties. Improving radial velocity accuracies are extending knowledge to lower planetary masses, observations spanning more than two decades are yielding improved statistics for large  $M_p$  and  $P$ , and observations in the infrared are extending the distributions to lower stellar mass. Kepler has provided a major advance in many aspects of multi-planet statistics for relatively short orbital periods. However, statistics in many regions remain poor.

**Occurrence rates for restricted samples** There are many studies of planet occurrence rates for restricted samples resulting from specific discovery methods, which are referenced elsewhere in this volume. These include statistics from radial velocity surveys (Chapter 2); from microlensing surveys (Chapter 5); from transit surveys, and especially from Kepler (Chapter 6); and from imaging surveys (Chapter 7).

Specific estimates have also been made for many other samples, including for binary and multiple stars

(§2.13.1); for post-main sequence stars (§8.9.1); and for Earth-like planets in the habitable zone (§11.7.4).

A compilation of papers dealing with such planet occurrence rates is maintained online at the NASA Exoplanet Archive (Table 1.4).

**Broader samples** Only limited efforts at characterising a more global planetary distribution function have been made. One example using results from microlensing, radial velocity and imaging observations, is described in Section 5.10.2.

In their estimates of the planets detectable by Gaia, Perryman et al. (2014a) simulated exoplanet occurrences in conjunction with the TRILEGAL population synthesis model of the Galaxy (box, page 380) according to the following dependencies:

(1) host star mass and metallicity: for  $M_\star > 0.6M_\odot$ , giant planet occurrence as a function of stellar mass and metallicity adopted that given by Johnson et al. (2010a), which was determined for  $0.5M_\odot < M_\star < 2.0M_\odot$  and  $[\text{Fe}/\text{H}] < 0.4$ . Perryman et al. (2014a) assumed that occurrences around stars with  $M_\star > 2.0M_\odot$  is equal to that at  $M_\star = 2.0M_\odot$ , and that the rate for stars with  $[\text{Fe}/\text{H}] > 0.4$  is equal to that at  $[\text{Fe}/\text{H}] = 0.4$ .

(2) planet mass and period distributions were assumed to be independent of metallicity. For each star, planets were drawn from the joint mass–period distribution given by Cumming et al. (2008), as determined from radial velocity surveys for GK stars. For  $M_p > 0.3M_J$  and  $P < 2000$  d, this followed a power-law fit

$$dN = C M^\alpha P^\beta d \ln M d \ln P, \quad (8.16)$$

with  $\alpha = -0.31 \pm 0.2$ ,  $\beta = 0.26 \pm 0.1$ , and the normalisation constant  $C$  such that 10.5% of solar type stars have a planet with mass in the range  $0.3 - 10M_J$  and orbital period 2–2000 d. For  $M_\star > 0.6M_\odot$ , this power law was extrapolated to cover the range  $0.1 - 15M_J$ , and to orbital periods up to 10 yr (for very wide orbits around A stars the best constraints are currently based on direct imaging). For  $P < 418$  d, the Kepler results for lower mass planets were used (Table 8.2), rather than extrapolating the Doppler-based distributions below  $0.3M_J$ .

(3) occurrence around low-mass M dwarfs,  $M_\star < 0.6M_\odot$ , adopted the double power law (Montet et al., 2014)

$$f(M_\star, [\text{Fe}/\text{H}]) = 0.039 M_\star^{0.8} 10^{3.8[\text{Fe}/\text{H}]}, \quad (8.17)$$

with a dependency on  $M_p$  (and flat in  $\log a_p$ ), consistent with both their observations and the microlensing observations, given by

$$dN \propto M_p^{-0.94} d \ln M_p d \ln a_p, \quad (8.18)$$

and extrapolated to cover the mass range  $0.1 - 15M_J$ .

(4) eccentricities of the 3d orbits were assumed to follow a Beta distribution (Equation 2.55) with  $a = 0.867$  and  $b = 3.03$ , ignoring any possible dependency on period.

*Table 8.2: Summary of the planet occurrence frequencies,  $f$ , as a function of planet mass and period adopted by Perryman et al. (2014a). For lower mass planets, this follows the size classification adopted by Fressin et al. (2013), along with the occurrence frequencies given in their Table 3. Their adopted  $R_p/R_\oplus$  limits were transformed to  $M_p/M_J$  using Equation 8.19. Notes: (a) from Fressin et al. (2013); (b) Fressin et al. (2013) give a single bin for planets in the range  $6 - 22R_\oplus$  (in parentheses), interpolated to give  $f = 0.0114$  for the restricted range  $0.1 - 0.3M_J$  to avoid overlap with the region defined by the Johnson–Cumming distribution; (c) the frequencies, from Johnson–Cumming, apply for a Sun-like star ( $1M_\odot$ ,  $[\text{Fe}/\text{H}] = 0$ ), and have been extrapolated to cover the range  $0.1 - 15M_J$  and  $P < 10$  yr.*

Class	$R_p$ ( $R_\oplus$ )	$M_p$ ( $M_J$ )	$P$	$f$
Earth <sup>a</sup>	0.8–1.25	0.002–0.007	0.8– 85 d	0.1840
super Earth <sup>a</sup>	1.25–2	0.007–0.018	0.8–145 d	0.2960
small Neptune <sup>a</sup>	2–4	0.018–0.033	0.8–245 d	0.3090
large Neptune <sup>a</sup>	4–6	0.033–0.077	0.8–418 d	0.0318
(giant) <sup>a,b</sup>	6–22	0.077–1.274	0.8–418 d	0.0524
'restricted' giant <sup>a,b</sup>		0.077–0.3	0.8–418 d	0.0114
giant <sup>c</sup>		0.1–0.3	418 d–10 yr	0.0388
giant <sup>c</sup>		0.3–15	2 d–10 yr	0.1339

(5) the distribution of low-mass planets ( $M_p < 0.3M_J$ ) used the joint period–radius distribution determined from the Kepler data for FGK stars by Fressin et al. (2013), which extends out to  $P = 428$  d for the largest planets.

(6) radii (from transit measurements) were converted to masses (from radial velocity measurements) using the following empirical relation, chosen to match the Fressin et al. (2013) occurrence rate (as a function of  $R_p$ ) to the Howard et al. (2010b) occurrence rate (as a function of  $M_p$ ) for  $P < 50$  d, and with  $M_p = 0.3M_J$  at  $R_p = 1R_J$

$$\begin{aligned} M_p &= 1.08 R_p^{3.45} & R_p \leq 1.5 \\ &= 3.17 R_p^{0.87} & 1.5 < R_p \leq 4.0 \\ &= 10.59 (R_p/4)^{2.07} & 4.0 < R_p \leq 6.0 \\ &= 24.51 (R_p/6)^{2.17} & 6.0 < R_p \end{aligned} \quad (8.19)$$

where  $M_p$  and  $R_p$  are expressed in Earth units.

(7) notable simplifications in their modeling was in the treatment of planets around binary stars, for which the secondary stars of binaries were ignored, and planets simulated around the primaries according to the occurrence distributions for single stars. For multi-planet systems, the Kepler distributions of Fressin et al. (2013) were partitioned into their designated mass bins, with at most one planet per mass bin generated for each star.

### 8.5.1 M dwarfs

Amongst studies of M dwarfs considered in other sections are surveys for nearby M dwarfs (§8.1.3), occurrence rates from radial velocity surveys (§2.8.4), from MEarth (§6.4.3), and the occurrence rate of giant planets jointly constrained by radial velocity and microlensing surveys (§5.10.2).



Also covered elsewhere are specific results on stellar flares (§8.10.6), their ultraviolet radiation environment (Segura et al., 2010; France et al., 2013), metallicity determinations and calibrations, including for Kepler targets (e.g. Rojas-Ayala et al., 2010; Neves et al., 2012; Mann et al., 2013a; Muirhead et al., 2014; Gaidos & Mann, 2014). and the effects on habitability (§11.7.1).

In addition to various considerations elsewhere, the appendices provide a concise narrative of studies and developments for all M dwarf planets, including the well-studied GJ 581, GJ 667, GJ 832, and GJ 3470.

### 8.5.2 Solar twins, analogues, and siblings

**Solar twins and analogues** In the search for habitable planets, attention has been given to ‘solar twins’, ‘solar analogues’, and ‘solar siblings’.

Although there is no precise definition, *solar twins* are (non-binary) stars which are essentially identical to the Sun in all astrophysical parameters: mass, age, luminosity, chemical composition, temperature, surface gravity, magnetic field, rotation velocity, microturbulence, and chromospheric activity. Solar twins *may be* those most likely to possess planetary systems similar to the solar system, and best-suited to host life forms based on carbon chemistry and water oceans.

In a less restricted definition, solar twins have been considered as those whose most fundamental parameters ( $T_{\text{eff}}$ ,  $\log g$ , and  $[\text{Fe}/\text{H}]$ ) lie within a certain range of solar values (e.g. Ramírez et al., 2010, and references), or more specifically as stars with  $0.95 < M/M_{\odot} < 1.05$  and  $P_{\text{rot}} > 14$  d (do Nascimento et al., 2014).

*Solar analogues* are yet more loosely defined. Some have taken them to describe stars that looked in the past, or will look in the future, very similar to the Sun, thus providing a perspective of the Sun at some other point in its evolution. In contrast, do Nascimento et al. (2014) uses the term to describe stars with  $0.9 < M/M_{\odot} < 1.1$ .

The systematic search for and study of solar twins and analogues started with the work of Hardorp (1978), who surveyed the near ultraviolet (360–410 nm) spectra of 77 solar-type stars, finding no G2V star which matches the properties of the Sun.

The pre-Hipparcos status of subsequent searches is reviewed by Cayrel de Strobel (1996). Starting with 109 photometric solar-like candidates, she was also unable to identify a ‘perfect’ twin, although two of the first three exoplanet systems discovered, 51 Peg and 47 UMa, were on the initial list. The G2 star HIP 79672 (HD 146233) at 14 pc comes very close to being such a twin, although with slightly higher luminosity and age (Porto de Mello & da Silva, 1997). The two G components of the binary 16 Cyg A/B (see also Schuler et al., 2011a) were considered to be the next closest twins.

Subsequent efforts to identify solar twins and other astrobiologically-interesting stars made extensive use of

the Hipparcos data (Porto de Mello et al., 2000; Pinho et al., 2003; Pinho & Porto de Mello, 2003; Galeev et al., 2004; King et al., 2005; Porto de Mello et al., 2006). These early studies suggested that HIP 79672 (18 Sco) and HIP 78399 are amongst the most promising solar twins. Of stars with planets on the Keck, Lick, and AAT Doppler planet-search programme at that time, Gray et al. (2006) found that only HD 186427 has properties close, rather than very close, to those of the Sun.

Various more recent solar twin planet search programmes are being undertaken (e.g. Ramírez et al., 2014c; Bedell et al., 2015; Nissen, 2015; Tucci Maia et al., 2016; dos Santos et al., 2016; Meléndez et al., 2017).

Based on these and other programmes, other stars variously classified as solar twins include HIP 11915 (Bedell et al., 2015); HIP 15527 (HD 20782, Yeager et al., 2011); HD 45184 (Nissen, 2015; Galarza et al., 2016); HIP 96548 (Meléndez et al., 2012); HIP 68468 (Meléndez et al., 2017); HIP 97769 (HD 188015, Yeager et al., 2011); HIP 100963 (Yana Galarza et al., 2016); HIP 102152 (Monroe et al., 2013); HIP 114328 (Meléndez et al., 2014); and Kepler-11 (Bedell et al., 2017).

With their broader definition of solar twins and analogues, do Nascimento et al. (2014) identified 34 Kepler stars as solar analogues, and 22 as solar twin candidates, while Nissen (2015) identified 21 solar twins.

**Abundance anomalies** Detailed spectroscopy shows that the Sun has a 20% depletion of refractory (condensation temperature  $T_C \gtrsim 900$  K) relative to volatile elements when compared with the majority of nearby solar twins. The abundance differences correlate strongly with the element’s condensation temperature, and the effect may be a signature of the planet formation that occurred more efficiently around the Sun (e.g. Meléndez et al., 2009; Ramírez et al., 2009, 2010; González Hernández et al., 2010; Schuler et al., 2011b; Meléndez et al., 2012; Ramírez et al., 2014b; Spina et al., 2016).

This peculiarity also holds in comparisons with solar analogues known to have close-in giant planets, while the majority of solar analogues found not to have such giant planets in radial velocity monitoring show the solar abundance pattern. Other results have confirmed and extended these findings (e.g. Rameau et al., 2013c; Meléndez et al., 2009; Chambers, 2010).

Chambers (2010), for example, argued that the solar photosphere is depleted in refractory elements compared to most solar twins, by typically  $4M_{\oplus}$  of Earth-like and carbonaceous-chondrite-like material. This deficit may have arisen because the Sun’s convection zone accreted nebular material depleted in refractory elements due to the formation of the terrestrial planets and ejection of rocky protoplanets from the asteroid belt. The fact that most solar analogues are missing  $0 - 10M_{\oplus}$  of rocky material compared to the most refractory-rich stars then provides an upper limit to the mass of rocky

terrestrial planets that they possess. The missing mass is correlated with stellar metallicity, again suggesting that the efficiency of planetesimal formation increases with stellar metallicity.

In discussions of habitability, radiogenic heat can play an important role, and one directly related to the mantle concentration of specific nuclides (§11.3.3). On Earth, Th and U make up 30–50% of the Earth's energy budget (Table 11.4), driving interior mantle convection and surface plate tectonics, which sustains a deep carbon and water cycle, and thereby aids in creating Earth's habitable surface. As a refractory element, the stellar abundance of Th is reflected in the terrestrial planet's concentration.

Unterborn et al. (2015) made a first investigation of the Th abundances in a number of solar twins and analogues, finding that  $\log \epsilon_{\text{Th}}$  varies from 59–251% that of solar, suggesting exoplanet systems may possess a greater energy budget with which to support surface-to-interior dynamics, and thus increasing their likelihood of being habitable compared to the solar system.

**Solar siblings** Stars that might have been born together with the Sun, within the same (putative) cluster or association (§12.1.2), are referred to as *solar siblings*. In contrast with solar twins, which are taken to have largely indistinguishable spectra regardless of origin, solar siblings must have identical age and chemical composition if they formed at the same time from the same gas cloud. They do not need to be Sun-like with respect to fundamental parameters such as effective temperature, mass, luminosity, or surface gravity.

Of relevance to practical searches, the orbit of the Sun can be 'reversed', based on a Galactic mass distribution model, to calculate its birthplace in the Galaxy. Solar siblings are then considered as being on a similar orbit around the Galactic centre. Some studies have suggested that perhaps 10–60 still exist within 100 pc of the Sun (Portegies Zwart, 2009; Mishurov & Acharova, 2011; Valtonen et al., 2015), with others significantly less optimistic (Mishurov & Acharova, 2011).

Various solar siblings have been proposed, some subsequently contradicted by later work. These include, chronologically, HD 28676 (Brown et al., 2010a), HD 83423 and HD 162826 (Bobylev et al., 2011), HD 28676, HD 83423, and HD 175740 (Batista & Fernandes, 2012), HD 162826 (Ramírez et al., 2014a), and HIP 40317 (Liu et al., 2015c). Further advances can be expected with Gaia (Martínez-Barbosa et al., 2016).

### 8.5.3 Other stellar classes

**Planets in the early Universe** Shchekinov et al. (2013) have suggested that conditions in the very early Universe, viz.  $z \sim 5-6$ , may allow the formation of planets in regions of sufficiently high dust-to-gas ratio (§10.6.2), and immediately following the first episode of metal production in Population III stars.

**Planets around hypervelocity stars** The disruption of a binary star by the massive black hole at the Galactic Centre, SgrA\*, can lead to the capture of one star around SgrA\* and the ejection of its companion as a *hypervelocity star*. Ginsburg et al. (2012) simulated a large number of different binary orbits around SgrA\*, studying the destiny of any originally accompanying planets. Possible outcomes include a planet ejected at a high speed, a hypervelocity star ejected with one or more planets still in orbit, planetary collision with its host star, or tidal disruption of the planet by SgrA\*, leading to a bright flare.

Detection of planets around hypervelocity (and runaway) stars has been evaluated by Fragione & Ginsburg (2017), who quantify the low probability of observing photometric transits, and the more optimistic prospects of discovering them with new-generation spectrographs along with Gaia and TESS.

## 8.6 Asteroseismology

Asteroseismology, the study of stellar oscillations, provides independent constraints on fundamental stellar parameters such as mass, density, radius, age, rotation period, and chemical composition. This is achieved by comparing patterns of observed oscillation frequencies with theoretical predictions based on corresponding models of stellar evolution. Such information is of value since stars with the same externally observable parameters ( $L_{\star}$ ,  $T_{\text{eff}}$ , and [Fe/H]) can have very different interiors as a result of their evolutionary histories.

Long, uninterrupted high-accuracy space-based photometry from CoRoT (launched in 2006) and especially Kepler (launched in 2009) have transformed the availability of suitable data for asteroseismic analysis. Various applications to exoplanet host stars have been made possible through improved knowledge of fundamental characteristics such as mass, radius, and age.

### 8.6.1 Principles

Stellar oscillations are predicted and observed over a wide range of mass and evolutionary states. Solar-like objects, high-amplitude  $\delta$  Scuti variables,  $\beta$  Cephei variables, and rapidly oscillating Ap stars have received particular seismological attention (e.g. Chaplin & Miglio, 2013; Christensen-Dalsgaard, 2013; Cunha, 2018).

In solar-type stars, oscillations are excited by turbulent convection (e.g. Christensen-Dalsgaard, 2004, Section 2.2). Standing pressure (or acoustic) waves are then trapped between the density decrease toward the surface, and the increasing sound speed toward the centre which refracts the downward propagating wave back to the surface. Similar oscillations are expected for all stars with significant surface convection, i.e. those on the cool side of the  $\delta$  Scuti instability strip.

Precise mode frequencies, typically in the range of 0.1–10 mHz (periods of order 1 min to a few hours), are detectable either by precision photometry (intensity changes) or by spectroscopy (radial velocity or equivalent width changes). Under favourable circumstances,

**Asteroseismology:** Non-radial oscillations were invoked more than 50 years ago to explain puzzling spectral characteristics of  $\beta$  Cephei stars. This led to the search and discovery of the 5-min oscillations in the Sun, and the development of *helioseismology* to probe its internal structure (Gough & Toomre, 1991; Christensen-Dalsgaard, 2002).

As applied to other stars, *asteroseismology* uses stellar oscillations, typically excited by convection or by the  $\kappa$  (opacity-driven) mechanism, to study their internal structure, dynamics, and evolutionary state (e.g. Christensen-Dalsgaard, 1984; Brown & Gilliland, 1994; Christensen-Dalsgaard, 2004; Aerts et al., 2010; Chaplin & Miglio, 2013).

Each *stellar oscillation mode* is characterised by three integers: the radial order  $n$ , the harmonic degree  $l$ , and the azimuthal order  $-l \leq m \leq l$ . Integers  $l$  and  $m$  determine the spherical harmonic component describing the properties of the mode as a function of co-latitude,  $\theta$ , and longitude,  $\phi$ , in a spherical polar coordinate system. The radial component of velocity, for example, can be expressed as (Christensen-Dalsgaard, 2004, eqn 1)

$$V = \mathcal{R} \left[ v_r(r) Y_l^m(\theta, \phi) \exp(-i\omega t) \right],$$

where  $Y_l^m(\theta, \phi) = c_{lm} P_l^m(\cos\theta) \exp(im\phi)$  is a spherical harmonic,  $P_l^m$  the associated Legendre function,  $c_{lm}$  a normalisation constant, and  $v_r(r)$  an amplitude function which depends only on radial distance  $r$ .

Since the surface of stars other than the Sun are (typically) unresolved, signal averaging over the stellar surface suppresses information from all but the modes of lowest degree, with  $l \leq 3$ . These involve the sound travel time across the stellar diameter, and conditions near the stellar surface and the convective boundary layer.

Frequencies generally scale as the inverse dynamical time scale (Christensen-Dalsgaard, 2004, eqn 2)

$$\omega_{\text{dyn}} = \left( \frac{GM_\star}{R_\star^3} \right)^{1/2}. \quad (8.20)$$

Detailed mode properties are determined by the dominant restoring force: either pressure caused by compression and rarefaction (p-modes), or buoyancy caused by density differences affected by gravity (g-modes). Waves propagate (or are damped) depending on specific local characteristic frequencies, viz. the acoustic (or Lamb) frequency  $S_l$ , and the buoyancy (or Brunt–Väisälä) frequency  $N$ .

individual mode frequencies can be determined with very high accuracy, despite their very small amplitudes, being at maximum some  $0.2 \text{ m s}^{-1}$  in radial velocity, or around  $5 \times 10^{-6}$  in broad-band photometric intensity.

**Space observations** Photometric observations from the ground are hampered by the atmosphere, while the long and uninterrupted observing periods necessary for the highest accuracy in frequency determinations are also limited by observing constraints. From space, MOST (§6.10.4), CoRoT (§6.5) and Kepler (§6.6) were all designed with photometric asteroseismology capabilities, in addition to their exoplanet transit detection modes. Asteroseismology investigations have also been made with HST-FGS (Gilliland et al., 2011b).

**Modeling the oscillations** Amplitudes and phases of the stellar oscillations are largely controlled by the near-surface layers. Frequencies are determined by the bulk sound speed, and the internal stellar density profile. Convective motions within the differentially rotating outer convective zone modify the star's temperature, density and velocity structure, while *convective overshooting*, caused by the momentum of cool sinking material into the deeper stable radiative regions, alters the structure of the *tachocline*, the transition region between the two. Stellar rotation, introduced as a rotation profile in the code solving for the adiabatic oscillation frequencies, further influences the fine structure of the frequency spectrum through its variation with stellar radius, and because of the resulting flows and instabilities which are also a function of the star's evolutionary state (Gough & Thompson, 1990).

Given these various complexities, the interpretation of an observed frequency spectrum proceeds via a comparison with theoretical stellar models, essentially providing a description of the stellar interiors via tests of the physical models used in their construction.

Various numerical codes are used to model stellar evolution according to initial mass, chemical composition, rotation, etc. Two which have been routinely applied to seismology targets are the Aarhus code (ASTEC, Christensen-Dalsgaard, 2008b) and the Toulouse–Geneva evolution code (TGEC, Vauclair, 2010). Both use similar foundations: the OPAL equation of state (Rogers et al., 1996), updated OPAL opacities (Iglesias & Rogers, 1996), and the NACRE nuclear reaction parameters (Angulo et al., 1999). Diffusion and He settling can be included. Convection is treated according to the widely-adopted mixing-length formulation of Böhm-Vitense (1958). Convective overshooting is parameterised to occur over a distance of  $\alpha_{\text{ov}}$  pressure scale heights, i.e. with  $\alpha_{\text{ov}} = 0$  describing its absence.

Corresponding codes for calculating oscillation frequencies include ADIPLS (Christensen-Dalsgaard, 2008a), and PULSE (Brassard et al., 1992). The former details the equations of *adiabatic stellar oscillations* (i.e. those for which the pulsation period is significantly less than the thermal time scale), the adopted approximations, and their numerical solution.

**Simplified expressions** While the precise frequencies of stellar oscillations depend on the detailed structure of the star, and on the physical properties of the gas, *asymptotic theory* (Christensen-Dalsgaard, 2004) leads to simplified expressions which are used for many seismological analyses in practice.

In the case of a non-rotating star, asymptotic analysis expresses the mode frequencies as (Christensen-Dalsgaard, 2004, eqn 7)

$$\nu_{n,l} = \Delta\nu \left( n + \frac{l}{2} + \alpha \right), \quad (8.21)$$

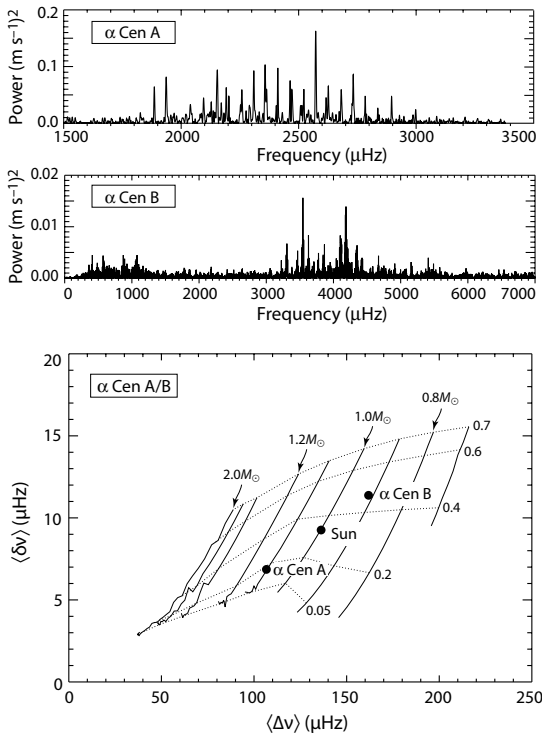


Figure 8.23: Top two: asteroseismic power spectra for  $\alpha$  Cen A and  $\alpha$  Cen B (on different frequency scales). Bottom: the corresponding asteroseismic Hertzprung–Russell diagram. Axes are the average small and large frequency separations,  $\langle \delta\nu \rangle$  and  $\langle \Delta\nu \rangle$  respectively. Solid lines are evolutionary tracks for fixed mass, and dashed lines show constant core-H content, related to age.  $\alpha$  Cen A is more massive and more evolved than the Sun, while  $\alpha$  Cen B is less massive and less evolved, results agreeing with traditional models of stellar evolution. From Bedding et al. (2004, Figure 1), Kjeldsen et al. (2005, Figure 4a), and Christensen-Dalsgaard (2004, Figure 3) respectively.

where  $n$  is the radial order and  $l$  is the angular degree,  $\alpha$  represents a phase shift sensitive to the properties of the near-surface layers, and where

$$\Delta\nu \simeq \left[ 2 \int_0^R \frac{1}{c} dr \right]^{-1} \quad (8.22)$$

is the inverse of the sound travel time across the stellar diameter, i.e. dependent on the mean stellar density. Hence the spectrum is uniformly spaced in radial order, with a spacing referred to as the *large separation*

$$\Delta\nu_{n,l} = \nu_{n,l} - \nu_{n-1,l} \sim \Delta\nu. \quad (8.23)$$

An inspection of Equation 8.21 implies that there is a frequency degeneracy in modes having the same value of  $n + l/2$ . A more detailed analysis shows that this implied degeneracy is not perfect, and that mode frequencies are further separated by the *small separation* determined by adjacent modes with  $n \rightarrow n - 1$  and  $l \rightarrow l + 2$ , viz.

$$\delta\nu_{n,l} = \nu_{n,l} - \nu_{n-1,l+2}. \quad (8.24)$$

Rotation, and other departures from spherical symmetry, introduce a further dependence of the oscillation frequencies on  $m$ . For a slowly rotating star (Christensen-Dalsgaard, 2004, eqn 11)

$$\omega_{n,l,m} \equiv 2\pi\nu_{n,l,m} = \omega_{n,l,0} + m \langle \Omega \rangle, \quad (8.25)$$

where  $m$  is the azimuthal order, and  $\Omega$  is the angular rotational velocity. This has been found to be a good approximation in the solar case, and provides for the possibility of determining stellar rotation periods from oscillation frequencies alone.

The inclination of the rotation axis affects the amplitudes of the different azimuthal degree modes, and can also be determined in principle (Gizon & Solanki, 2003). For rapidly rotating stars, higher-order effects further complicate the frequency spectrum (Gough & Thompson, 1990).

The asteroseismic Hertzsprung–Russell diagram relates the average small separation,  $\langle \delta\nu \rangle$ , to the average large separation,  $\langle \Delta\nu \rangle$ . This can be used to estimate stellar parameters such as mass and, through central hydrogen abundance as a proxy, age (Figure 8.23).

Model frequency structures are often presented in the form of an échelle diagram (e.g. Figures 8.24 and 8.25), in which the frequency is expressed as

$$\nu_{n,l} = \nu_0 + k\Delta\nu + \tilde{\nu}_{n,l}, \quad (8.26)$$

where  $\nu_0$  is some reference frequency, and  $k$  is an integer such that  $0 < \tilde{\nu}_{n,l} < \Delta\nu$ . The spectrum is then divided into segments of length  $\Delta\nu$ , and  $\tilde{\nu}_{n,l}$  plotted against  $\nu_0 + k\Delta\nu$ . The frequencies would then line up vertically if the asymptotic expression given by Equation 8.21 were precisely valid.

**Accuracy of stellar parameters** In the context of the CoRoT observations, Mulet-Marquis et al. (2009) generated models to derive the uncertainties of fundamental stellar parameters for a given accuracy of oscillation frequency determination. They estimated accuracies of 1–7% in  $M_\star$ , 1–3% in  $R_\star$ , and 2–10% in  $L_\star$ .

Simulations by Kjeldsen et al. (2009) give comparable uncertainties of 5% in  $M_\star$ , 2–3% in  $R_\star$ , 1% in  $\rho_\star$ , and 5–10% for ages relative to the total time on the main sequence. Applied to 33 Kepler hosts with well-determined pulsation frequencies, Silva Aguirre et al. (2015) estimated uncertainties of 3.3% in  $M_\star$ , 1.2% in  $R_\star$ , 1.7% in  $\rho_\star$ , 14% for ages, along with 14% in distance (constrained from bolometric luminosities).

Examples of the self-consistent determination of  $M_\star$ ,  $R_\star$ ,  $T_{\text{eff}}$ ,  $M_{\text{bol}}$ , and hence distances, which can then be compared to Hipparcos distances to demonstrate their fidelity, are given explicitly for  $\eta$  Boo and  $\kappa^1$  Boo (Bedding et al., 1998); and 22 Kepler targets (Silva Aguirre et al., 2012).

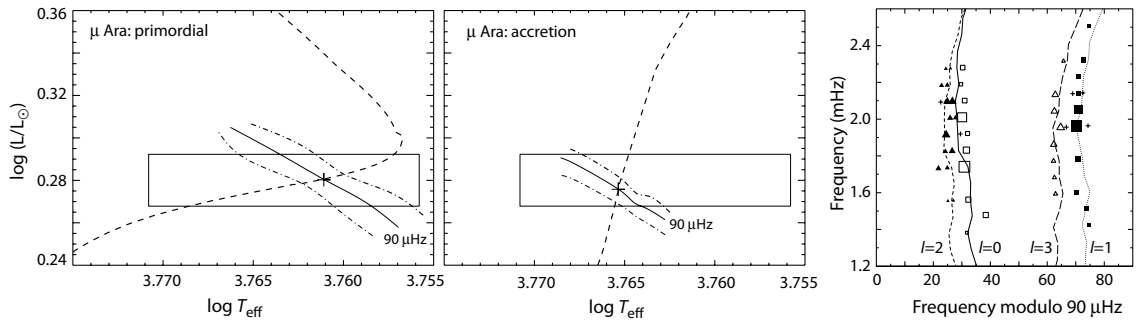


Figure 8.24: Asteroseismology of the Doppler-planet host  $\mu$  Ara. Left and middle: evolutionary tracks (dashed lines) for assumed primordial overmetallic and self-enrichment/accretion scenarios, respectively. The three oblique lines correspond to asteroseismic separations of  $90 \mu\text{Hz}$  (as observed, solid line), as well as  $89 \mu\text{Hz}$  (higher curve) and  $91 \mu\text{Hz}$  (lower curve), and the cross corresponds to the favoured model. Error boxes correspond to the Hipparcos-based luminosity and adopted  $T_{\text{eff}}$ . Right: échelle diagram for the overmetallic model. Lines represent the theoretical modes indicated. Symbols represent their observational counterparts, with sizes proportional to signal-to-noise. From Bazot et al. (2005, Figures 1–3), reproduced with permission © ESO.

The conversion of mode amplitudes in any particular spectral band to bolometric amplitudes, for comparison with theoretical models, are quantified in the case of the Kepler observations by Ballot et al. (2011a).

### 8.6.2 Application to CoRoT and Kepler targets

Availability of long uninterrupted stretches of space data, notably from CoRoT and Kepler, has allowed for many advances in asteroseismology beyond that of explicit relevance to exoplanet host stars.

For CoRoT, for example, these techniques have been applied to OB stars (Degroote et al., 2010), joint ground- and space-based observations (Rainer et al., 2012; Bognár & Paparó, 2012).

For Kepler, a few specific results are discussed in more detail in Chapter 6. These include, by way of illustration only, constraints on M giants (Stello et al., 2014), and on 13 000 red giants (Sharma et al., 2016). A joint asteroseismic and spectroscopic survey, APOKASC, combining Kepler asteroseismology and APOGEE spectroscopy, provides  $T_{\text{eff}}$ ,  $[M/H]$ ,  $\log g$ ,  $M_{\star}$ , and  $R_{\star}$  for 1916 red giants in the Kepler field (Pinsonneault et al., 2014)

### 8.6.3 Application to exoplanet host stars

Many applications of asteroseismology of relevance to exoplanet host stars have been reported. The Fourth Azores International Advanced School in Space Sciences was, for example, devoted to the field (Campante et al., 2018). A recent review is given by Huber (2018). Only a few examples are given hereafter, divided into topics to illustrate the different applications, although the techniques and scientific objectives often overlap.

**Primordial or self-enriched metallicities** Oscillation frequencies and amplitudes can be compared with stellar evolutionary models to determine whether the observed metallicity is a bulk or surface property, thus

providing independent evidence as to whether the high metallicity of exoplanet host stars is primordial, or a result of self-enrichment.

The four-planet system  $\mu$  Ara (Pepe et al., 2007) shows the common attribute of high metallicity compared to stars without detected planets. From a Fourier transform of the HARPS radial velocity time series, Bouchy et al. (2005a) identified 43 oscillation modes, with harmonic degrees  $l = 0 - 3$ . To first order,  $L_{\star}$  is constrained by the Hipparcos parallax of  $65.5 \pm 0.8$  mas.

Evolutionary simulations Bazot & Vauclair (2004); Bazot et al. (2005) suggest that the metal-rich models have a convective core, while the accreting models do not. These internal structural differences lead to specific predicted signatures for the  $l = 0$  and  $l = 2$  modes. Although the seismic analysis provides precise and independent constraints on  $L_{\star}$  and  $T_{\text{eff}}$  (Figure 8.24), the crucial frequency region from 2.5–2.7 mHz had only low signal-to-noise, and interpretation in terms of either primordial or accretion models could not be resolved unambiguously. Further analysis has been reported by Sorianio & Vauclair (2010).

For  $\iota$  Hor, some 25 solar-type oscillation modes were detected with HARPS (Laymand & Vauclair, 2007). The metallicity, helium abundance, and age derived from the seismic analysis were found to be characteristic of the Hyades cluster. Vauclair et al. (2008) concluded that the metallicity is therefore primordial.

**Stellar masses** The determination of stellar masses for giant stars is complicated by the fact that evolutionary tracks over a wide range of masses converge to the same region of the Hertzsprung–Russell diagram (e.g. North et al., 2017a). Hatzes & Zechmeister (2008) measured stellar oscillations in three planet-hosting giant stars: HD 13189, HD 62509 ( $\beta$  Gem), and HIP 75458 ( $\iota$  Dra). They showed that their periods (in the range 0.1–5 d) and

Table 8.3: Asteroseismology analysis for the Kepler field transit host star HAT-P-7. For three values of the overshoot parameter,  $\alpha_{\text{ov}}$ , the model fit gives the stellar parameters which minimise  $\chi^2_{\text{v}}$  along the evolutionary tracks shown in Figure 8.26. Data are from Christensen-Dalsgaard et al. (2010, Table 2).

$\alpha_{\text{ov}}$	$L_{\star}$ ( $L_{\odot}$ )	$M_{\star}$ ( $M_{\odot}$ )	$R_{\star}$ ( $M_{\odot}$ )	Age (Gyr)	$T_{\text{eff}}$ (K)	$\chi^2_{\text{v}}$
0.0	5.91	1.53	1.994	1.758	6379	1.08
0.1	5.81	1.52	1.992	1.875	6355	1.04
0.2	5.87	1.50	1.981	2.009	6389	1.00

radial velocity amplitudes (in the range 5–85 m s<sup>-1</sup>) are consistent with solar-like p-mode oscillations, and derived stellar mass estimates consistent with, but independently of, isochrone models.

**Stellar densities** From HST-FGS observations of the p-modes of the transiting host HD 17156, Gilliland et al. (2011b) derived  $\rho_{\star} = 0.5301 \pm 0.0044 \text{ Mg m}^{-3}$ . This can be compared with the direct determination also possible from transit observations, which have yielded results, in rather good agreement, of  $0.522 \pm 0.02 \text{ Mg m}^{-3}$  (Nutzman et al., 2011b). The improved asteroseismic density yields  $M_{\star} = 1.285 \pm 0.026 M_{\odot}$ ,  $R_{\star} = 1.507 \pm 0.012 R_{\odot}$ , and a stellar age  $\tau = 3.2 \pm 0.3 \text{ Gyr}$ .

**Stellar ages** Stellar ages from asteroseismology are inferred from the star’s location in the theoretical Hertzsprung–Russell diagram. Examples of the modeling and resulting age uncertainties are given for HD 17156 (Lebreton, 2012), for a sample of 33 Kepler stars (Silva Aguirre et al., 2015), and for HD 19994 (94 Cet; Deal et al., 2017).

**Stellar rotation** Constraints on rotation have been described, for example, for HD 52265 (Gizon et al., 2013).

**Stellar obliquity** Asteroseismic constraints on the rotational splitting for the multi-planet host stars Kepler-50 and Kepler-65 demonstrate that their rotation axes are nearly perpendicular to the line-of-sight, with  $|90^{\circ} - i_{\text{s}}| < 15^{\circ}$  for Kepler-50, and  $< 25^{\circ}$  for Kepler-65 (Chaplin et al., 2013). The orbital inclinations of the planets in each (transiting) system are also near  $90^{\circ}$ , implying only small differences in the stellar and orbital inclination angles, and low stellar obliquities.

For Kepler-410, in addition to the excellent precision on the various fundamental stellar parameters ( $M_{\star} = 1.214 \pm 0.033 M_{\odot}$ ,  $R_{\star} = 1.352 \pm 0.010 R_{\odot}$ ,  $\tau = 2.76 \pm 0.54 \text{ Gyr}$ , yielding  $R_{\text{p}} = 2.838 \pm 0.054 R_{\oplus}$ ), rotational splitting of the pulsation modes yields a stellar inclination  $82.5^{+7.5}_{-2.5} \text{ deg}$ , and a resulting low obliquity (Van Eylen et al., 2014). The échelle diagram is shown in Figure 8.25.

**Stellar surface gravities** Lower limits on surface gravities, for host stars with no detected oscillations, may provide some parameter constraints on the planetary systems (Campante et al., 2014).

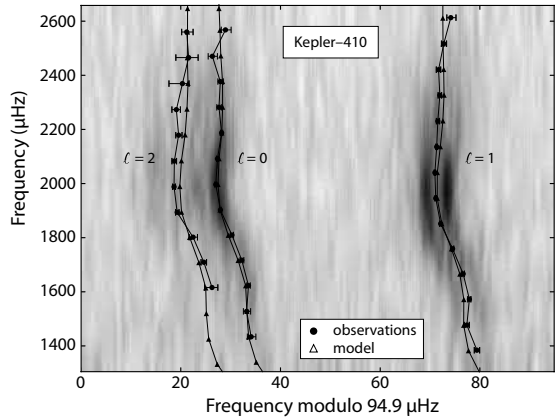


Figure 8.25: Asteroseismological échelle diagram of the power spectrum of Kepler-410, with observed and modeled frequencies for angular degrees  $l = 0 - 2$ . From Van Eylen et al. (2014, Figure 4), by permission of IOP Publishing/AAS.

**Planet radii for transiting planets** Large uncertainties on the determination of transiting planet radii can result from the uncertainties on stellar radii to which they are normalised. Christensen-Dalsgaard et al. (2010) reported Kepler asteroseismology results for the three exoplanet host stars identified by ground-based transit surveys in the Kepler field: HAT-P-7, HAT-P-11, and TrES-2, all expected to show solar-like oscillations at observable amplitudes. The frequency spectrum for HAT-P-7 was used in models for each of three assumed values of the overshoot parameter  $\alpha_{\text{ov}}$  (Table 8.3, and Figure 8.26). The best fit is given by  $\alpha_{\text{ov}} = 0.2$ , resulting in  $R_{\star} = 1.981 R_{\odot}$  from the asteroseismic analysis.

**Planet masses for imaged companions** The masses of companions detected by direct imaging are estimated from their brightness. Since giant planets fade as they radiate away the heat of their formation, mass estimates are correspondingly sensitive to the estimated age of the host star. For HR 8799 (§7.10.2), Marois et al. (2008b) estimated the age of the host star as 30–160 Myr using a number of indirect lines of argument, giving implied companion masses in the range 7–10  $M_{\text{J}}$ .

The host star is a  $\gamma$  Doradus-type pulsational variable. This is a class of main sequence star in the lower part of the classical instability strip with  $P \sim 1 \text{ d}$ . Moya et al. (2010a) used the g-mode pulsation spectrum to estimate its age using asteroseismology, where its metallicity and age both have a significant influence on the corresponding buoyancy-type restoring force. They estimated a much higher age of around 1 Gyr, albeit dependent on the unknown inclination of the stellar rotation axis. This age revision would raise the companion masses to the brown dwarf range.

**Planetary excitation of g-modes** A planet orbiting a solar-type star at a radius such that the Keplerian orbital

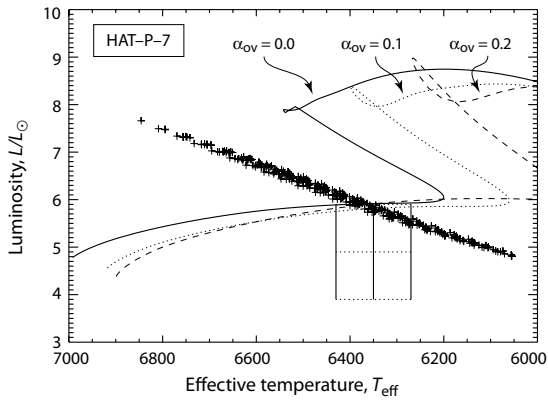


Figure 8.26: Theoretical Hertzsprung–Russell diagram for the transit host star HAT-P-7, with evolutionary tracks showing fits to three assumed values of the overshoot parameter  $\alpha_{\text{ov}}$ . Models indicated ‘+’ minimise the difference between the computed and observed frequencies. The box is centred on the  $L_{\star}$  and  $T_{\text{eff}}$  values given by Pál et al. (2008), with a size matching their errors. From Christensen-Dalsgaard et al. (2010, Figure 3), by permission of IOP Publishing/AAS.

frequency,  $\omega_k = \sqrt{[G(M_{\star} + M_p)/a^3]}$ , is half the frequency of a given resonant mode of the star, may excite g-modes as a result of their gravitational interaction. Dynamical tides raised by the planet on the star are dissipated due to turbulent viscosity in the convective zone and to radiative damping in the radiative core, as modeled in coalescing binary stars (Kokkotas & Schafer, 1995; Alexander, 1987). Even for close-in planets the effects are generally small (Terquem et al., 1998), but certain configurations may be observable (Berti & Ferrari, 2001).

**Other individual observations** Other individual exoplanet host star investigations have been made for various CoRoT targets, e.g. HD 52265 (Soriano et al., 2007; Ballot et al., 2011b; Escobar et al., 2012; Lebreton & Goupil, 2014), and HD 49933 (Liu et al., 2014c).

Fundamental properties of many Kepler host stars have similarly been derived (e.g. Huber et al., 2013b).

**Expectations from TESS** Simulations for the long uninterrupted and finely-sampling high-accuracy photometry with TESS (§6.8.1) suggest that asteroseismology of known host stars will detect solar-like oscillations in a few dozen (mainly subgiant stars but also in a smaller number of F dwarfs), in up to 200 low-luminosity red giants, and in over 100 solar-type and red giants. This would imply a threefold improvement in the asteroseismic yield of exoplanet-host stars compared Kepler (Campante et al., 2016b).

#### 8.6.4 Planet and exoplanet seismology

**Jupiter and Saturn** For planets themselves, non-radial oscillations of Jupiter and Saturn also provide seismological probes, with effects due to their solid

cores, (differential) rotation, and ellipticity (Vorontsov & Zharkov, 1981; Vorontsov, 1981; Marley, 1991). For Jupiter, early attempts to observe oscillations from the ground with CFHT (Mosser et al., 2000), were followed by detection of acoustic p-modes through Fourier-based radial velocity measures (Gaulme et al., 2011).

For Saturn, gravitational perturbations associated with its oscillation modes generate density waves (from radial and azimuthal forces) and bending waves (from vertical forces) that propagate through its rings (Shu, 1984). One of the consequences is that the ring structure (§12.5.12) is a probe of Saturn’s oscillations, a specific diagnostic technique that has been termed *kronoseismology* (Hedman & Nicholson, 2013; Fuller et al., 2014).

Marley & Porco (1993) argued that some of the previously unexplained (spiral) features in Saturn’s C and D-rings observed with Voyager (Rosen et al., 1991a,b) were produced at Lindblad resonances with the gravitational perturbations associated with the planet’s oscillation modes. This interpretation has been confirmed with subsequent radio and ultraviolet occultation data from Cassini (Hedman & Nicholson, 2013; Fuller et al., 2014; Fuller, 2014).

**Exoplanets** While global oscillations of giant exoplanets are unlikely to be detected in the foreseeable future, excitation mechanisms more vigorous than in Jupiter or Saturn, with more significant pulsation amplitudes, may be possible. Le Bihan & Burrows (2013) estimated characteristic frequencies  $\nu_0$  as a function of  $M_p$ ,  $R_p$ , core mass, and envelope heavy element mass fraction, finding

$$\nu_0 \sim 164 \left( \frac{M_p}{M_J} \right)^{0.48} \mu\text{Hz} \quad R_p = R_J, M_p = 0.5 - 15 M_J \quad (8.27)$$

$$\nu_0 \sim 164 \left( \frac{R_p}{R_J} \right)^{-2.09} \mu\text{Hz} \quad M_p = M_J, R_p = 0.9 - 2 R_J. \quad (8.28)$$

### 8.7 Stellar variability

Aside from asteroseismology, many other stellar variability studies have exploited the Kepler observations (e.g. Basri et al., 2010, 2011; Balona et al., 2011; Debosscher et al., 2011; Ciardi et al., 2011; Uytterhoeven et al., 2011; Arkhypov et al., 2015), with a number focused on the several thousand eclipsing binaries (e.g. Coughlin et al., 2011; Prša et al., 2011; Slawson et al., 2011; Matijević et al., 2012; Conroy et al., 2014a,b; LaCourse et al., 2015; Kirk et al., 2016a).

Others have followed as by-products of other transit searches, including in the fields of CoRoT (e.g. Lebzelter, 2011), and SuperWASP (e.g. Smalley et al., 2011b).

The discovery that certain manifestations of stellar brightness variations observed by Kepler, termed *flicker*, are correlated with surface gravity and stellar density, are discussed further in Section 6.29.2.

## 8.8 Stellar multiplicity

The relationship between planetary systems and stellar multiplicity is a complex one connecting the formation of binary and multiple star systems, the formation of planetary systems, and the various observational techniques used to characterise them. The subject is considered under the formation of planets in multiple stellar systems (§10.12), and under imaging searches around binary stars, and imaging constraints on stellar multiplicity (§7.9.4).

## 8.9 White dwarfs

White dwarfs represent the terminal evolutionary stage for 90% of the stellar population. If planets robustly survive the demise of their parent star, they would be common around white dwarfs. They would be interesting targets for direct imaging because of the favourable planet–white dwarf flux ratio (Ignace, 2001; Burleigh et al., 2002; Livio et al., 2005; Gould & Kilic, 2008).

Searches using timing techniques, based on orbital modulation of oscillations of the white dwarf itself, are considered in Section 4.3.2. White dwarfs also make attractive transit targets because of their small radii (and hence large transit depths), although faintness and short transit durations (as a result of their small size) both conspire against detection (§6.3.4).

Two other related developments have more recently underlined the importance of white dwarfs to exoplanet research. The discovery that debris disks are reasonably common around white dwarfs provides evidence both that planetesimals exist around them, and that the process of collisional attrition is ongoing. The related discovery of significant metal pollution in many white dwarf photospheres also demonstrates that a significant mass of collisional debris is being continuously accreted onto the white dwarf, with spectral analysis providing diagnostics of its chemical composition.

### 8.9.1 Survival considerations

Whether planetary companions to white dwarfs exist, having survived the red giant branch and asymptotic giant branch phases, will depend on initial orbit separations, stellar mass-loss rate and total mass loss, tidal forces, and interactions with the ejected material.

Planets in initial orbits within the final extent of the red giant envelope will be engulfed and migrate inwards (Livio & Soker, 1984; MacLeod et al., 2018). Stellar evolution models accounting for tidal decay, orbit shrinking, and stellar spin-up during this phase guide potential observability of the star's evolving reflex motion, or transit signatures (perhaps by PLATO), during the final few hundred years before engulfment (Meynet et al., 2017).

Planets further out will have a greater chance of survival, migrating outwards as mass is lost from the

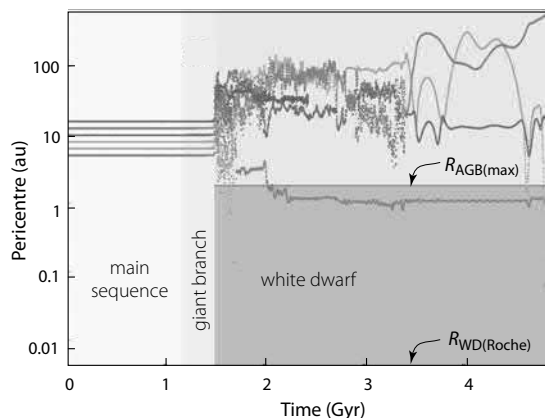


Figure 8.27: Post main-sequence survival simulations based on a ‘packed’ 6-planet configuration comprising an original sequence of ‘UNUNUN’ Uranus–Neptune mass planets. For this specific simulation, ‘dynamical unpacking’ (orbit crossing) of the orbital pericentres occurs promptly at the end of the giant branch phase, with the innermost subsequently undergoing a deep radial incursion. From Veras et al. (2016b, Figure 7d), © Oxford University Press.

central star. If significant mass is lost instantaneously, then the planet will escape the system if its orbital velocity exceeds the instantaneous escape velocity. In practice, the dynamical time scale for a planet to react to even very significant mass-loss rates is measured in decades, small compared to even the shortest evolutionary phases (Burleigh et al., 2002, eqn 3).

Accordingly, planetary orbits should simply expand adiabatically, with a  $1M_{\odot}$  progenitor evolving to become a  $0.5M_{\odot}$  white dwarf leading to orbits expanding by a factor two. In the process, some stable orbits might nevertheless become unstable (Debes & Sigurdsson, 2002), while the system may be disrupted if velocity kicks during the red giant phase are asymmetric (Heyl, 2007).

As a result, orbits with initial  $a \geq 0.7$  au will remain larger than  $R_{\star}$  at all evolutionary stages (box, page 414), and white dwarfs could therefore potentially host surviving planets with  $P \geq 2.4$  yr. Massive white dwarfs could host even shorter period planets if the primary is the product of a gravitationally driven merger which leaves behind a remnant debris disk (Livio et al., 1992).

Subsequent survival analyses have included considerations of eccentricity and habitability (e.g. Nordhaus et al., 2010; Bear et al., 2011b; Kunitomo et al., 2011; Fossati et al., 2012; Passy et al., 2012; Adams et al., 2013b; Nordhaus & Spiegel, 2013; Veras et al., 2013b; Mustill et al., 2014; Villaver et al., 2014; Veras et al., 2016b).

**Unpacking of Kepler-type packed systems** An understanding of the dynamical behaviour of more realistic planetary systems during post-main sequence evolution became more pressing with the discovery of ongoing white dwarf accretion processes attributed to plane-



**White dwarfs:** White dwarfs are the end point of stellar evolution for stars of  $M_{\star} \lesssim 8M_{\odot}$ , with different routes leading to the same fate. Theory predicts that most have a bulk composition dominated by C or C–O cores, and a narrow mass distribution peaking around  $0.58M_{\odot}$  (Koester et al., 1979; Bergeron et al., 1992; Finley et al., 1997). The canonical mass for He ignition in the cores of red giants (the He flash) is  $\sim 0.46 - 0.48M_{\odot}$ , so that white dwarfs with lower masses are inferred to have He cores.

Since the main-sequence lifetime of low-mass progenitors exceeds the Hubble time, low-mass white dwarfs are considered to have formed differently, viz. by Roche lobe overflow in a binary star system, in which the low-mass He core is exposed as a result of mass transfer to the secondary before the white dwarf progenitor reaches the tip of the red giant branch. For the high-mass tail, theory predicts interiors dominated by Ne and Mg (Panei et al., 2000).

The classification scheme DA, DB, DAZ, etc. consists of an initial D, a letter describing the dominant spectral feature, and optional letter(s) describing secondary features (McCook & Sion, 1999, Table 1). Thus DA dwarfs have atmospheres dominated by H I; DB by He I; DC have a continuous spectrum; DO are dominated by He II; DZ by metal lines; and DQ by carbon. Thus DAZ are H-dominated, with metal lines. A number can be used to encode  $T_{\text{eff}}$ .

White dwarfs span a vast temperature range, with the H-rich class extending from 170 000 K to 4500 K, and with temperature providing a direct luminosity and age indicator. Their temperatures intersect instability regions analogous to those seen around the main sequence, and span the DA dwarfs (including the very common pulsating ZZ Ceti stars), the DB dwarfs, and the DO dwarfs (including the pulsating GW Vir stars).

The catalogue of McCook & Sion (1987) included 1279 objects, the fourth edition 2249 (McCook & Sion, 1999), with 14 000 in the 2016 on-line version. The SDSS DR7 White Dwarf Catalogue comprises 20 000 objects, with 13 000 DA and 1000 DB spectral types (Kleinman et al., 2013). Gaia will increase the numbers tenfold to 200 000 complete to  $V \sim 20$  mag, including thousands of cool white dwarfs (Perryman et al., 2001; Carrasco et al., 2014).

White dwarfs are common in the solar neighbourhood, although survey completeness falls rapidly with distance. Some 200 are known within 20 pc (Holberg et al., 2002; Sion et al., 2009; Giammichele et al., 2012; Subasavage et al., 2017).

tary debris as evidenced in their photospheres (§8.9.4). More detailed simulations then target an improved understanding of the type of bodies, and the type of material, that can be delivered to their photospheres.

Veras et al. (2016b) extended earlier analyses, based on one or two equal mass planets, to 450 numerical integrations of the Kepler-type packed planetary systems of unequal mass, extending over a Hubble time (14 Gyr). In addition to gravitational planet–planet interactions within the multi-planet system, effects of stellar mass loss and radiation are included, while the secondary effects of tides and general relativity are not. Resulting dynamical behaviour of the originally packed system is complex, and highly dependent on initial conditions.

A flavour is given by one of the simulations shown in Figure 8.27. Starting with 6 planets of Uranus/Neptune masses, this particular simulation illustrates both the *dynamical unpacking* (orbit crossing) which occurs at the end of the giant branch phase, as well as an example of a deep radial incursion, inside the maximum radius of the asymptotic giant branch. Many other types of complex dynamical behaviour are illustrated in their sequence of simulations.

They concluded that, unlike in the giant planet case which preferentially feature ejections, terrestrial-planet unpacking often does not trigger instability (engulfments, ejections and collisions), and provides a more dynamic, constantly shifting evolution throughout the white dwarf phase; this result is independent of the mass variation amongst planets. Furthermore, the smaller the dispersion in planetary mass, the closer those planets may be perturbed towards the white dwarf. Finally, rather than ejections, terrestrial-planet systems preferentially feature planet–planet collisions, with the conse-

quent expectation of more potentially polluting debris existing in terrestrial-planet systems.

**Post-common-envelope binaries** Survival and planet detection of post-common-envelope binaries is described in the context of timing studies (box, page 113).

**Post-evolutionary formation** In specific cases, evidence for planets may exist despite arguments against planetary survival through the red giant and asymptotic giant branch phases (e.g. GD 356, Wickramasinghe et al., 2010). In such cases, planets could have formed from the circumstellar disk of a disrupted He or CO core during a rare merger of two white dwarfs, analogous to the ms binary pulsar PSR 1257+12 (§4.2.2). The survey results of Koester et al. (2014), however, suggest that such a formation scenario is not common. A related post-evolutionary formation mechanism, starting from tidal disruption debris, is described by Bear & Soker (2015).

**Planets and planetary nebulae** The emission nebulae known as *planetary nebulae* arise during the red giant phase, when the outer layers of the star are expelled by strong stellar winds and illuminated by the ultraviolet radiation from the hot luminous stellar core. The term is a misnomer, originating from William Herschel's observations in the 1780s that, viewed through his telescope, they resembled the rounded shapes of planets.

The majority are not spherically symmetric, and the wide variety of shapes and features are variously attributed to binary central stars, stellar winds and magnetic fields. However, the role of substellar companions, and especially planets, in shaping their morphology was emphasised by Soker (1996). He argued that, on average, several substellar objects must be present around most

**Survival of the solar system planets:** Various studies have been made of the Sun's future beyond its H-burning main sequence, and the consequences for planetary orbits and engulfment, tidal interactions, and gravitational escape as a result of mass loss (e.g. Jorgensen, 1991; Sackmann et al., 1993; Soker, 1994; Rybicki & Denis, 2001; Spiegel & Madhusudhan, 2012; Veras & Wyatt, 2012; Adams et al., 2013b; Veras, 2016b).

Sackmann et al. (1993) predicted that, while still on the main sequence, the Sun's luminosity will reach  $1.1L_{\odot}$  in 1.1 Gyr, and  $1.4L_{\odot}$  in 3.5 Gyr, at which points 'moist greenhouse' and 'runaway greenhouse' catastrophes are predicted by cloud-free climate models (Kasting, 1988). It reaches  $2300L_{\odot}$  and  $R \sim 170R_{\odot}$  on the red giant branch (about 7.8 Gyr hence), engulfing Mercury.

After core He burning, it climbs the asymptotic giant branch, reaching its largest radius of  $213R_{\odot}$  (0.9 au) at the first thermal pulse. By this point its mass has reduced to  $0.6M_{\odot}$ , and the orbits of Venus and Earth have moved out to 1.22 and 1.69 au. It reaches its peak luminosity of  $5200L_{\odot}$  at the fourth thermal pulse, finally reaching a white dwarf mass of  $0.54M_{\odot}$ , by which time Venus and Earth will have moved out to 1.34 and 1.85 au. Schröder & Connors (2008) suggest that the Earth will not survive engulfment.

main sequence stars with  $M_{\star} \lesssim 5M_{\odot}$  to explain their morphologies, and that the presence of four gas giant planets in the solar system is accordingly the rule rather than the exception. Soker (1997) further classified 458 planetary nebulae according to the processes inferred to result in axisymmetric winds, suggesting that some 55% require substellar companions (i.e., planets and brown dwarfs) via a common-envelope phase (the other classes being: progenitors that did not interact with any companion, 10%; progenitors that interact with stellar companions that avoided a common envelope, 11%; and progenitors that interact with stellar companions via a common-envelope phase, 23%).

De Marco & Soker (2011) suggested a model in which only 20% of all  $1 - 8M_{\odot}$  stars create a planetary nebula (reducing the need for planetary shaping) and, assuming that planets can only shape mildly elliptical structures, concluded that 20% of all planetary nebulae were shaped by planetary and other substellar interactions. Further adjustments are detailed by Sabach & Soker (2018).

### 8.9.2 Imaging

The ratio of temperatures and bolometric luminosities of the planet and white dwarf in a circular orbit are given by (Ignace, 2001)

$$\frac{T_p}{T_{wd}} = (1 - A_B) \left( \frac{R_{wd}}{2a} \right)^{(1/2)}, \quad (8.29)$$

$$\frac{L_p}{L_{wd}} = \frac{R_p^2 T_p^4}{R_{wd}^2 T_{wd}^4} = \left( \frac{R_p}{2a} \right)^2 (1 - A_B), \quad (8.30)$$

where  $T_p$ ,  $T_{wd}$  are the planet's equilibrium temperature and white dwarf effective temperature respectively,  $R$

are the radii,  $a$  is the orbital radius, and  $A_B$  is the planet's Bond albedo. The bolometric brightness contrast between the planet and star is therefore a function only of  $R_p$ ,  $a$ , and  $A_B$ .

White dwarf luminosities are some 1000 times smaller than solar-type stars (because of their smaller sizes), and the ratio of bolometric luminosities may be a factor  $10^3 - 10^4$  more favourable for imaging compared to the situation for a late-type main-sequence star. For hot white dwarfs, the atmosphere of a Jovian planet will also be photoionised, leading to the emission of hydrogen recombination lines which may be detectable spectroscopically (Chu et al., 2001).

**Wavelength choice** Imaging prospects are best in the infrared, where the ratio of the planet's thermal emission to that of the (rapidly cooling) white dwarf is largest (for a discussion of cooling times see, e.g., Salaris et al., 2013). For  $T_{wd} = 10000$  K, and a  $1R_J$  planet with  $P \approx 100$  d, the  $10 \mu\text{m}$  flux at its Wien peak may be comparable to the emission of the white dwarf well into its Rayleigh–Jeans tail (Ignace, 2001).

At the same time, the Roche limit imposes a maximum temperature and hence brightness of an orbiting planet. For  $M_{wd} = 1M_{\odot}$  and  $R_{wd} = 1R_{\oplus}$ , a Jupiter-like planet cannot orbit closer than  $\sim 24R_J$ , so that its temperature is limited to  $T_p \lesssim 0.04T_{wd}$ .

**Imaging searches** Imaging searches, aiming to detect planetary mass companions around nearby white dwarfs, have been largely unsuccessful (box, page 415).

A single object is listed in the NASA Exoplanet Archive imaging discoveries, WD 0806–661 (GJ 3483) discovered from Spitzer–IRAC observations by Luhman et al. (2011). The companion mass is consistent with Jeans-mass fragmentation, considered the most likely formation mechanism (Rodriguez et al., 2011).

Meanwhile, a number of white dwarfs are known as wide companions to stars hosting exoplanets. Specifically, Mugrauer & Neuhäuser (2005) used VLT–NACO to establish that a stellar mass companion discovered by Els et al. (2001) to be orbiting the star GJ 86A is a cool white dwarf. There are also white dwarf companions to HD 147513A (Mayor et al., 2004) and HD 27442A (Mugrauer et al., 2007). These systems provide some evidence that planets can survive post-main sequence evolution, albeit at distances of  $\geq 10 - 20$  au.

In summary, while the most sensitive searches to date could detect companions with  $M_p \gtrsim 5M_J$ , only one such object orbiting a white dwarf has been found. Their paucity is consistent with the conclusions of McCarthy & Zuckerman (2004), whose infrared coronagraphic search of 178 stars at Steward and Lick found that no more than 3% of main-sequence stars harbour  $5 - 10M_J$  planets orbiting between 75–300 au.

**Imaging searches around nearby white dwarfs:** Clarke & Burleigh (2004) and Burleigh et al. (2006) searched for common proper motion companions using adaptive optics imaging to  $J = 24$  using Gemini and WHT. Debes et al. (2005a) used HST–NICMOS and Gemini–Altair–NIRI imaging of G29–38, placing limits of  $16M_J$  and  $6M_J$  at separations 3–12 au and  $> 12$  au respectively; further Spitzer observations are reported by Reach et al. (2005). Debes et al. (2005b) used HST–NICMOS to search seven DAZ white dwarfs within 50 pc to limits of  $\sim 10 - 18M_J$ . Friedrich et al. (2005) used HST–NICMOS to search seven Hyades white dwarfs, where adiabatic expansion is expected to have resulted in orbital distances of 25 au and magnitudes  $JH \approx 20.5 - 23.3$  mag. Hansen et al. (2006) used Spitzer–IRAC to observe 14 hot white dwarfs. Mullally et al. (2007) used Spitzer–IRAC to observe 124 bright white dwarfs, placing limits of  $5M_J$  for eight stars, and  $10M_J$  for 23 stars. Kilic et al. (2009) used Spitzer–IRAC to observe 14 white dwarfs of high-mass stellar remnants, giving limits of 5– $10M_J$ . Mullally et al. (2009) used Spitzer–IRAC to place an upper limit of 5– $7M_J$  on a possible companion inferred from pulse timing variations. Kilic et al. (2010) used Spitzer–IRAC for a search around 14 low-mass white dwarfs. Hogan et al. (2011) describe the DODO survey (Degenerate Objects around Degenerate Objects).

**Astrometric searches** Ground-based trigonometric parallax programmes from RECONS have identified new white dwarfs within 25 pc, but without identifying specific substellar companions (Subasavage et al., 2007, 2008, 2009, 2017). Gaia is expected to increase the total known numbers tenfold to 200 000, complete to  $V \sim 20$  mag, including thousands of cool white dwarfs (Perryman et al., 2001; Carrasco et al., 2014). Planet detection through their astrometric signature may be possible, depending on occurrence rates and mass distributions which are as yet unknown.

**Microvariability from Kepler** From 14 hot (DA, DB) white dwarfs observed with Kepler, Maoz et al. (2015) found at least five showing periodic (2 h–10 d) variability at 60–2000 ppm. Excluding rotation, magnetic cool spots, or planet reflection as being common to all, they suggest that the periodicity could mainly arise from ultraviolet metal-line opacity associated with accretion of rocky material, a phenomenon now seen in some 50% of hot white dwarf photospheres (§8.9.4). They concluded that, even if planet reflection is the cause in just a few of the seven cases, it would also imply that hot Jupiters are common around them.

### 8.9.3 Dust disks

Searches for extended dust (debris) disks, including space-based infrared searches with Spitzer and more recently with WISE, have been more successful. The presence of such disks is inferred from their large mid-infrared spectral excess. Such objects are sometimes classified as DAZd white dwarfs.

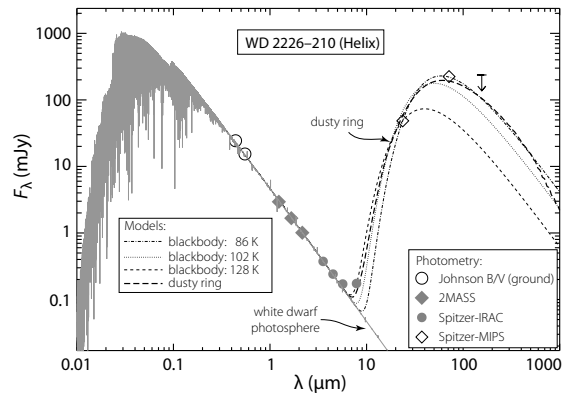


Figure 8.28: Spectral energy distribution of WD 2226–210, the central white dwarf in the Helix Nebula. Photometry is from the sources indicated. Models are for the white dwarf photosphere (grey line), blackbody excess with  $T \sim 86 - 128$  K, and for a dusty ring, at 35–150 au (long-dashed line). From Su et al. (2007, Figure 3), by permission of IOP Publishing/AAS.

They are frequently accompanied, and their presence sometimes signalled, by heavy element pollution in the white dwarf photospheres (§8.9.4). Their existence is attributed to tidal disruption of comets (Debes & Sigurdsson, 2002), asteroids (Jura, 2003, 2006, 2008), or planetesimals more generally (Dong et al., 2010).

**Discoveries** Early discoveries include G29–38 (Graham et al., 1990; Jura, 2003; Gänsicke et al., 2006; Reach et al., 2009; Xu et al., 2014); GD 362 (Becklin et al., 2005; Kilic et al., 2005); WD 2226–210 (Su et al., 2007; Dong et al., 2010); and GD 40 (Jura et al., 2007; Klein et al., 2010).

WD 2226–210, at the centre of the Helix planetary nebula, has been suggested as a prototype (Figure 8.28). Observed with Spitzer, the dust ring extends 35–150 au from the central white dwarf (interior to the helix structure), has a total mass of  $\sim 0.13M_{\oplus}$ , and is inferred to be replenished through collisional fragmentation of planetesimals (Su et al., 2007; Dong et al., 2010).

More recent discoveries have resulted from the WISE–WIRED (WISE InfraRed Excesses around Degenerates) Survey, including GALEX J1931+01 (Debes et al., 2011a). The WIRED Survey is sensitive to substellar objects and dusty debris around white dwarfs out to distances exceeding 100 pc, well beyond the completeness level of local white dwarfs.

From a cross-correlation of the SDSS DR7 White Dwarf Catalogue with WISE, 2MASS and UKIDSS, Debes et al. (2011b) reported WISE detections of 344 ‘naked’ white dwarfs, 1020 candidate white dwarf/M dwarf binaries, 42 candidate white dwarf/brown dwarf binaries, and 52 white dwarf+dust disk systems. A further 28 WISE candidates were reported by Hoard et al. (2013).

Rocchetto et al. (2015) searched for disks around 134 single white dwarfs with Spitzer–IRAC, finding a total of 5 systems, three known previously, yielding a nom-

inal  $3.7^{+2.4}_{-1.0}\%$  in the post-main-sequence range  $T_{\text{eff}} = 17\,000\text{--}25\,000\text{ K}$  with detectable circumstellar dust. With complementary HST–COS observations indicating that 27% show metals in their photosphere (Koester et al., 2014), only currently explained by ongoing accretion from circumstellar material (§8.9.4), means that some 90% of disks escape detection in the infrared, presumably due to their small emitting surface area.

Searches in 381 white dwarfs with archival Spitzer–IRAC data (Barber et al., 2016) yielded 15 dusty systems, three new (including the hottest known, WD 0010+280), with peak occurrence at 12.5% for  $M_{\text{WD}} = 0.7\text{--}0.75M_{\odot}$  (corresponding to  $\sim 3M_{\odot}$  progenitors), and falling off for more massive stars, mirroring predicted planet occurrence rates as a function of stellar mass.

Numerous other white dwarf disk candidates have been reported (e.g. Farihi et al., 2009, 2010b; Melis et al., 2010b; Farihi et al., 2012a; Girven et al., 2012; Kilic et al., 2012; Li et al., 2017b). Suggestions that the nearest white dwarf, Sirius B, might have a mid-infrared excess (Bonnet-Bidaud & Pantin, 2008) are unconfirmed (Skemer & Close, 2011; Bond et al., 2017a).

**Disk precession** From 12 yr of optical spectroscopy of the disk system SDSS J1228+1040, morphological variations of the 860 nm Ca II triplet lines could be ascribed, using Doppler tomography (§6.18.6), to a periodic precession of the disk, with  $P = 24\text{--}30$  yr, consistent with relativistic precession (Manser et al., 2016b).

**Inner disk heating** In many systems, inferred inner disk radii are so close to the white dwarf that particles directly exposed to starlight must be heated above 1500 K, and hence liable to sublimation. Rafikov & Garmilla (2012) showed that their high metal vapour pressure actually raises their sublimation temperature 300–400 K higher than in their protoplanetary analogues, allowing particle survival at higher temperatures, and resulting in superheated inner rims with  $T \sim 2500\text{--}3500\text{ K}$ .

Particles migrating through the rim toward the white dwarf rapidly sublimate, then shield the disk from further excess heating, making the survival of solids possible close to the white dwarf. Their model requires that disk particles are composed of Si-rich material such as olivine,  $(\text{Mg, Fe})_2\text{SiO}_4$ , with sizes  $300\ \mu\text{m}\text{--}0.3\text{ m}$ .

Material build-up at the sublimation radius can lead to *runaway accretion*, and accretion rates orders of magnitude higher than expected from Poynting–Robertson drag alone (§12.5.13), consistent with the highest measured rates (Rafikov, 2011b; Metzger et al., 2012b).

### 8.9.4 Elemental pollution

In addition to the direct detection of accompanying dusty disks, there is further compelling support for the existence of (proto-)planetary systems or rocky planetesimals accompanying a number of white dwarfs (of

**Heavy element pollution of white dwarfs:** A history of the field of heavy element pollution of white dwarf photospheres is given by Zuckerman (2015). He suggests that the first observational evidence for the existence of an extra-solar planetary system came a century ago from one such ‘polluted’ star, van Maanen 2 (vMa 2, van Maanen, 1917, 1919), although van Maanen did not know that he had observed a white dwarf, nor was their nature understood.

Today, vMa 2 is considered the DZ spectral class prototype, with a  $R = 20\,000$  VLT–UVES spectrum showing that the pollution is refractory-rich (with lines of only Fe, Ca, and Mg) yet H deficient (Napiwotzki et al., 2003).

Other white dwarfs with photospheric metals were discovered. It was soon appreciated that their intense gravity should cause heavy elements to sink rapidly (Schatzman, 1945), with elements heavier than He pulled into the interiors on time scales up to several orders of magnitude shorter than their cooling ages (Fontaine & Michaud, 1979).

A replenishing source is therefore required. Initially, accretion from the interstellar medium was favoured (see, e.g., Farihi et al., 2010a), although subsequent observations (e.g. Zuckerman & Becklin, 1987b; Zuckerman et al., 2003; Gänsicke et al., 2006; Zuckerman et al., 2007; Farihi et al., 2010a) and theoretical work (e.g. Graham et al., 1990; Debes & Sigurdsson, 2002; Jura, 2003) have shifted the accretion paradigm to rocky asteroidal debris.

Studies have since suggested that heavy elements in an isolated white dwarf with  $T_{\text{eff}} \sim 5000\text{--}20\,000\text{ K}$  is evidence for the presence of a wide-orbit planetary system. In most, perhaps all, cases the planetary system contains at least one rocky debris belt and one major planet (e.g. Veras et al., 2013b; Mustill et al., 2014). The gravitational field of the planet(s) can perturb the asteroid orbits so that rocky asteroidal material is eventually accreted onto the white dwarf (e.g. Jura & Young, 2014).

The largest number of identified heavy elements is 16 in the case of GD 362, demonstrating that the debris was broadly terrestrial-like (Zuckerman et al., 2007).

types DAZ, DBZ, and DZ), evidenced by heavy element pollution of their photospheres (box, page 416).

Because of the short metal-sinking time scales, this heavy element pollution is taken as indicating that material accretion onto the white dwarfs is ongoing, with spectral analysis yielding insight into the chemical composition of the accreted material.

Farihi et al. (2012b) described metal-enriched white dwarfs as representing astrophysical traps for exoplanetary debris, and therefore ‘acting as detectors that can yield the bulk composition of planetary building blocks that orbit intermediate mass stars’. Reviews of the field are given by Jura & Young (2014), and Farihi (2016).

**Origin of the pollutant metals** The favoured model for the origin of this material is the tidal disruption of a large asteroid analogue (Jura, 2003), perturbed into high eccentricity by an unseen body such as a major planet, perhaps through secular instabilities such as the Lidov–Kozai mechanism in wide ( $\geq 100$  au) stellar binaries (Debes & Sigurdsson, 2002; Bonsor et al., 2011; Debes et al., 2012; Frewen & Hansen, 2014; Antoniadou

& Veras, 2016; Bonsor et al., 2017; Brown et al., 2017b; Petrovich & Muñoz, 2017; Stephan et al., 2017).

Models include detailed collisional cascades near the Roche limit (Kenyon & Bromley, 2017a), which may also feed the generation of gaseous disks through the vapourisation of small particles (Kenyon & Bromley, 2017b). Specific considerations pertain to closer-separation stellar binaries, for which stellar winds can generate an additional matter stream (Veras et al., 2018).

Gravitational scattering triggering the liberation of a moon into a white dwarf grazing orbit may provide another dynamical pathway for matter to reach the photosphere (Payne et al., 2016, 2017).

Delivery invoking planet–planet interactions becomes problematic at cooling times of several Gyr, for which Lidov–Kozai oscillations due to a binary companion, and exacerbated by stellar mass loss, may provide an explanation, and may motivate searches for such companions around old polluted white dwarfs (Hamers & Portegies Zwart, 2016b).

Mid-infrared spectroscopy reveals disk matter that is silicate rich and carbon poor (Jura et al., 2009; Reach et al., 2009), while stellar spectroscopy reveals atmospheric pollution by refractory-rich and volatile-poor material (Jura, 2006; Farihi et al., 2010a, 2011a; Jura & Xu, 2013). High-resolution optical spectroscopy of the disk-contaminated stars reveals terrestrial-like abundances (Zuckerman et al., 2007; Klein et al., 2010).

**Sinking and accretion rates** Various estimates of the inferred accretion rates, for various elements, have been made (e.g. Gänsicke et al., 2012; Bergfors et al., 2014; Manser et al., 2016a). Although broadly consistent, they are sensitive to the white dwarf temperatures because of the associated dependency of the depth of the convection zone. DAZ white dwarfs with  $T_{\text{eff}} \gtrsim 11\,000$  K possess tiny convection zones (if at all), and have correspondingly short metal sinking time scales, on the order of days (Koester, 2009), providing ongoing and instantaneous measures of the infall of a given heavy element, which can often exceed  $10^5 \text{ kg s}^{-1}$  (Farihi et al., 2012b). In contrast, for the coolest DAZ stars and the DBZ stars in general, the assumption of a steady state is uncertain owing to larger diffusion time-scales from correspondingly deeper convection zones (Paquette et al., 1986).

DBZ stars, for example, can retain atmospheric metals for some  $10^5 - 10^6$  yr, and while they cannot yield instantaneous accretion rates, their sizeable convection zones contain the integrated signatures of accretion, a substantial mass of metals acquired within the last few sinking time-scales. DBZ stars accordingly provide a historical record of accretion and, importantly, a minimum mass for the destroyed parent body or bodies (Jura, 2006; Farihi et al., 2010a; Klein et al., 2010).

Farihi et al. (2012b) estimated that the high-rate accretion time scale is likely  $\lesssim 10^3$  yr, such that a search of

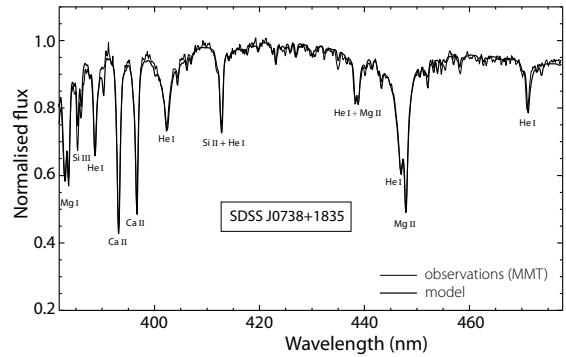


Figure 8.29: Part of the spectrum of white dwarf SDSS J0738+1835, illustrating heavy element accretion. The MMT data (thin line, part of a data set acquired with Gemini, Keck, Magellan, MMT, SDSS, GALEX and Spitzer) is superposed on a model spectrum (thick line), for  $T_{\text{eff}} = 13950 \pm 100$  K,  $\log g = 8.4 \pm 0.2$  dex, comprising a C/O core and He and H layer thicknesses of  $q(\text{He}) = 10^{-2}$  and  $q(\text{H}) = 10^{-10}$ . Lines other than those identified are from Fe. The rapid sinking time of the heavy elements within the white dwarf photosphere argues for ongoing accretion, and places robust constraints on the accretion rate. From Dufour et al. (2012, Figure 7), by permission of IOP Publishing/AAS.

10 000 DA stars would be needed to detect one in a high state lasting 100 yr. Gaia may be capable of identifying a single white dwarf accreting in a high state as it should (they estimate) identify some  $10^6$  white dwarfs, and thus yield at least 10 000 metal-polluted candidates.

Farihi et al. (2012b) derived different accretion rates for DA and DB white dwarfs, ranging from  $10^{2.5} - 10^{6.5} \text{ kg s}^{-1}$  for DAZ and from  $10^{2.5} - 10^{8.5} \text{ kg s}^{-1}$  for DBZ white dwarfs, corresponding to a few asteroid masses accreted in a few Myr. These (unexpected) differences disappear if the effect of thermohaline convection (§8.4.3), in addition to gravitational settling, is taken into account (Deal et al., 2013b,a). Caveats to this interpretation are given by Xu et al. (2014, Section 5.1).

**Other polluted white dwarfs** Other highly-polluted atmospheres include G241–6 (Zuckerman et al., 2010); GALEX J1931+01 (Debes et al., 2011a; Melis et al., 2011b); NLTT 43806, enriched in Al but not Fe (Zuckerman et al., 2011); the He-dominated PG 1225–079 and HS 2253+80, with evidence for Earth-like composition and large asteroid mass accretion (Klein et al., 2011); the 120 kG magnetic field (Zeeman splitting) G77–50 (Farihi et al., 2011c); GD 61 with evidence of material differentiation from Spitzer (Farihi et al., 2011a, 2013b); SDSS J0738+1835, with a composition similar to that of the bulk Earth (Figure 8.29), and evidence for the tidal disruption of a Ceres-mass body (Dufour et al., 2010, 2012); GD 40 and G241–6 observed with HST–COS (Jura et al., 2012); four white dwarfs from HST observations (Gänsicke et al., 2012); GD 362 and PG 1225–079 observed with HST–COS (Xu et al., 2013);

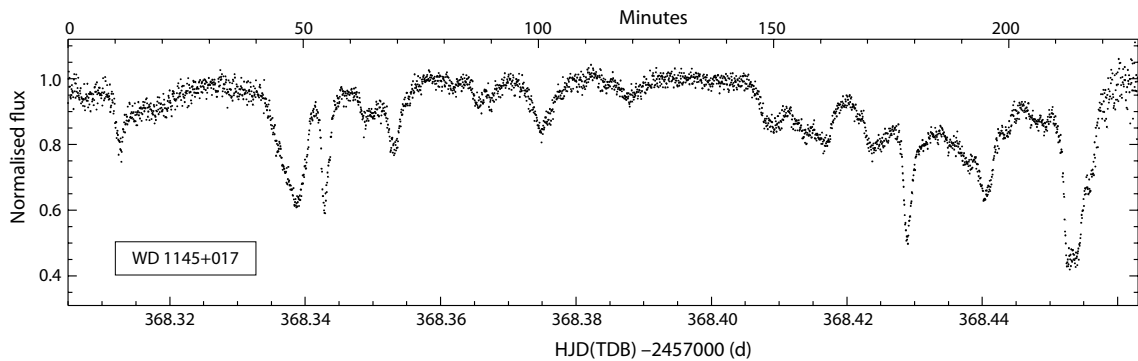


Figure 8.30: Material transiting the white dwarf WD 1145+017, observed with ULTRASPEC at the TNT (Thai National Telescope). High-speed (5 s) photometry, over 3.9 h on 2015 December 11, illustrates the complex nature of the multiple transit events. Many of the broader transits display sub-structure suggestive of the superposition of several shorter events, while some can be tracked in phase across multiple nights. From Gänsicke et al. (2016, Figure 1), by permission of IOP Publishing/AAS.

G29–38 and GD 133 observed with HST–COS (Xu et al., 2014), and SDSS J1043+0855, also observed with HST–COS and Keck–HIRES (Manser et al., 2016a; Melis & Durfor, 2017).

**Fragmentation around WD 1145+017** The paradigm of pollution arising from accretion has been reinforced by observations of minor bodies transiting the polluted WD 1145+017, discovered during campaign 1 of the Kepler K2 mission (§6.6.3), and found to be evolving significantly thereafter. The white dwarf is orbited by disintegrating planetesimals with  $P \sim 4.5 - 4.9$  h, close to the Roche limit for a weak rubble pile. Varying transit depths of 40–60% and asymmetric profiles are indicative of a small object with a cometary tail of dusty effluent, a few times the size of the white dwarf (Figure 8.30).

It has since been observed intensively, in the optical, at high time resolution, using spectropolarimetry, and at X-ray wavelengths, while models further suggest the accretion of differentiated (mantle) material (Vanderburg et al., 2015a; Alonso et al., 2016; Gänsicke et al., 2016; Rappaport et al., 2016; Veras et al., 2016a; Xu et al., 2016a; Zhou et al., 2016a; Croll et al., 2017; Gurri et al., 2017; Gary et al., 2017; Hallakoun et al., 2017; Kjurkchieva et al., 2017a; Veras et al., 2017a; Farihi et al., 2018; Rappaport et al., 2018a; Xu et al., 2018).

**Occurrence rates** Farihi et al. (2010a) found at least 3.5% of all white dwarfs harbour remnants of terrestrial planetary systems, and hence that  $\geq 3.5\%$  of main sequence A and F stars build terrestrial planets. Of 117 cool DA white dwarfs, Barber et al. (2012) found a slightly higher debris disk fraction of 4.3%.

From 85 DA white dwarfs observed with HST–COS (cooling ages 20–200 Myr, and  $T_{\text{eff}} = 17000 - 27000$  K), Koester et al. (2014) found at least 27% accreting. Together with previous studies, and assuming bulk Earth abundances, they determined accretion rates ranging

from a few hundred  $\text{kg s}^{-1}$  to a few  $10^5 \text{ kg s}^{-1}$ , with no trend in cooling age from 40 Myr to 2 Gyr.

No cases of strong metal-pollution are found for  $T_{\text{eff}} > 23000$  K, where the luminosity is presumed sufficient to vaporise circumstellar dust grains. From consideration of their main sequence progenitors, Koester et al. (2014) conclude that the formation of rocky planetary material is common around late B and A stars.

Their finding that only one of 14 targets with  $M_{\text{wd}} > 0.8M_{\odot}$  is currently accreting, suggests that such stars indeed generally result from double-degenerate mergers, and the merger disks do not commonly reform large planetesimals or otherwise pollute the remnant.

The presence of heavy elements in the atmospheres appears to be suppressed for white dwarfs with a binary companion within  $\sim 1000$  au, suggesting in turn that circumprimary planet formation is suppressed in main sequence A–F stars, even in the case of rather remote secondary companions (Zuckerman, 2014).

**Hyades** The Hyades open cluster contains some dozen white dwarfs (e.g. Humason & Zwicky, 1947; Luyten, 1954, 1956; Böhm-Vitense, 1995; Zuckerman et al., 2013), while the present-day luminosity function predicts that it should contain  $\sim 25-30$  (Chin & Stothers, 1971). The discrepancy between observed and predicted numbers is attributed to evaporation from the cluster (e.g. Weidemann et al., 1992; Eggen, 1993a,b; Perryman et al., 1998), and a number of such escaping white dwarfs are now recognised (Schilbach & Röser, 2012; Tremblay et al., 2012; Zuckerman et al., 2013).

Farihi et al. (2013c) found evidence for rocky planetesimals in two Hyades white dwarfs, WD 0421+162 (EG 36) and WD 0431+126 (EG 39). Zuckerman et al. (2013) found pollutants in LP 475–242 and GD 31. Other Hyades searches have focused on planet detection (Su et al., 2006; Cieza et al., 2008; Farihi et al., 2008; Mizusawa et al., 2012).

**Water content** Farihi et al. (2010a) found that the DZA class are polluted by both metals and hydrogen, suggesting a common origin for both (because of the comparable metal-to-metal sinking time scales), indicating that DZA star pollution by H<sub>2</sub>O-rich minor planets may be semi-continuous on Myr time scales, and hence providing constraints on the frequency and mass of H<sub>2</sub>O-rich, extrasolar planetesimals (e.g. Malamud & Perets, 2016, 2017a,b). Atmospheres with H<sub>2</sub>O-rich pollutants include GD 61 (Farihi et al., 2013b), SDSS J1242+5226 (Raddi et al., 2015), WD 1536+520 (Farihi et al., 2016), and GD 16 and GD 17 (Gentile Fusillo et al., 2017).

In contrast, evidence for an impacting planetesimal on Ton 345, with  $M \gtrsim 0.6M_{\text{Vesta}}$  appears to have been C-rich and H<sub>2</sub>O-poor, suggesting that it was compositionally similar to those Kuiper belt objects with relatively little ice (Jura et al., 2015; Wilson et al., 2015a).

For a sample of nearby luminous white dwarfs, Jura & Xu (2012) found that the summed accretion rate of heavy atoms exceeds that of H by more than  $\times 1000$ . As an ensemble, this sub-population of extrasolar asteroids has little H<sub>2</sub>O, being a factor of 20 drier than CI chondrites, the most primitive meteorites. Their observations provide indirect support for the importance of a snow line in disks where rocky planetesimals form.

### 8.9.5 Evidence for differentiation

Planetesimal composition is determined as a 3-step process (§10.4): (i) during nebular condensation, element incorporation is a function of local temperature and pressure; (ii) differentiation may redistribute elements within it, with lithophiles (Al, Ca, Ti) enhanced in the crust and siderophiles (Fe, Mn, Cr, Ni) settling to the core; (iii) collisions lead to stripping and blending of cores and crust, redistributing elements within the entire planetary system. In the solar system, chondrites are a consequence of nebular condensation, while achondrites and primitive achondrites have experienced post-nebular processing (O'Neill & Palme, 2008).

Accreted white dwarf photospheric compositions typically resemble that of bulk Earth, with at least 85% by mass composed of O, Mg, Si, and Fe; C and H<sub>2</sub>O-ice are only trace constituents (Jura & Young, 2014; Farihi et al., 2016; Manser et al., 2016a). Detailed results suggest that differentiation, leading to Fe-rich cores and Al-rich crusts, is common (Figure 8.31). Except for some high Ca abundances, the more exotic objects predicted by Bond et al. (2010), such as C/Si- or Ca/Al/O-dominated, have not yet been found (Jura & Xu, 2012).

More specifically, their composition appears to result from processes similar to those controlling the formation and evolution of objects in the inner solar system. Evidence points to extrasolar planetesimals having experienced igneous differentiation (e.g. Jura et al., 2013; Jura & Young, 2014; Veras et al., 2017a) with individual accreted parent bodies inferred to consist of an Fe-rich core (Gänsicke et al., 2012), an Fe-poor mantle (Farihi et al.,

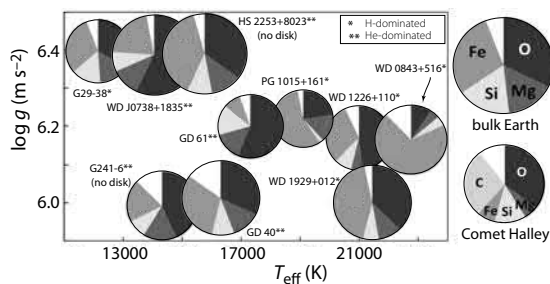


Figure 8.31: Compilation of all polluted white dwarfs with detections of at least O, Mg, Si, and Fe (compositional references given in the original figure caption) including, for comparison, bulk Earth (Allègre et al., 2001), and Comet Halley (Jessberger et al., 1988). All except two white dwarfs also possess dust disks. Circle sizes correlate with accretion rate (not to scale). O, Mg, Si, and Fe are always the dominant elements in a variety of extrasolar planetesimals, resembling bulk Earth. No C-rich planetesimals similar to Comet Halley have been identified. From Xu et al. (2014, Figure 18), by permission of IOP Publishing/AAS.

2013b), an Al-rich crust (Zuckerman et al., 2011) or a mixture of core and crustal material (Xu et al., 2013). Internal heating and subsequent melting, attributed to the decay of <sup>26</sup>Al, can help to explain these results (Jura et al., 2013). Accretion of a Kuiper-belt object analogue onto WD 1425+540, with N observed in the debris for the first time, was reported by Xu et al. (2017b).

At the same time, no purely crustal material has been detected, viz. where Si/O are the dominant pollutants; rather, accreted material appears to be composed of blends of core, mantle and crust (Jura & Young, 2014).

**Evidence for plate tectonics: Sr and Ba** The possibility that rocky exoplanets experience plate tectonics has received some attention (§11.7.3). Assessments have been made of the conditions under which plate mobility and subduction might occur, as a function of mass, size, structure and composition. By analogy with Earth (§12.3.5), this effort is partly motivated by the recognition that plate tectonics is likely to affect a planet's habitability. Both the planet's surface conditions and thermal structure are dependent on its tectonic regime, itself resulting from the driving forces and resistive strength of the lithosphere.

Jura et al. (2014) suggested that an indirect search for plate tectonics is possible because of a unique spectral signature in an externally polluted white dwarf given by the abundances of Ca, Sr and Ba. Reddy et al. (2003) had already reported abundances of 27 elements in 181 nearby F and G main sequence stars spanning a wide age range. Ca, Sr and Ba abundances are almost always within 0.10 dex of the solar value, suggesting that planets generally form from an extrasolar nebular of approximately solar composition. Furthermore, because the condensation temperatures of Ca, Sr and Ba are nearly identical (Lodders, 2003), separation of these elements may be expected to occur only in post-nebular physical processes.

Noting that, relative to Ca, both Sr and Ba are markedly enriched in Earth's continental crust compared to the basaltic crusts of other differentiated rocky bodies of the solar system (§12.3.5), Jura et al. (2014) suggested that the  $n(\text{Ba})/n(\text{Ca})$  ratio accordingly serves as a proxy for the existence of plate tectonics. They derived  $n(\text{Ba})/n(\text{Ca})$  from Keck spectra for two polluted white dwarfs known to have non-chondritic abundances: GD 362 (Zuckerman et al., 2007; Xu et al., 2013) and PG 1225-079 (Klein et al., 2011; Xu et al., 2013). While Jura et al. (2014)

found that at most only a small fraction of the pollution is from crustal material that has experienced the distinctive elemental enhancements induced by Earth-analogue plate tectonics, future targets can be expected to provide further constraints.

## 8.10 Star–planet interactions

The term *star–planet interaction* covers various phenomena, treated in various places in this text.

### 8.10.1 Overview of the various interactions

With smaller planet–star separations, the effects of the star’s gravity, its electromagnetic and particle radiation, and its magnetic field become stronger, affecting the planet’s figure, tidal and magnetic dissipation, and atmosphere. Interactions are particularly pronounced for planets orbiting within a few 0.1 au, and include:

*Tidal effects:* within a few 0.1 au, tides are raised on the planet by the star, and on the star by the planet (§10.11). Tides lead to spin–orbit resonances including tidal locking (§10.11.5), tidal heating of the planet (§10.11.9), and spin-up of the star (§10.11.8). Modifications to transit light curves include effects of planet prolateness (§6.14.18), tidally-induced gravity darkening (§6.14.19), tidally-excited stellar pulsations (§6.14.20), tidal disruption, engulfment (§6.14.21), disintegration (§6.14.22), and various secular timing effects (§6.19).

*Stellar radiation:* a high flux of X-rays and extreme ultraviolet radiation, emitted by young stars and decreasing with stellar age, has various effects on close-in planets. It can lead to atmospheric erosion and mass loss (§11.4.5). It results in (asymmetric) atmospheric heating (§11.4.1), which affects atmospheric circulation and chemical equilibrium, with consequences for their spectroscopic signatures (§11.6), and orbital phase curves (§6.15). It can contribute to atmospheric inflation (§6.28.4), and to heating of planetary interiors. Gelman et al. (2011) showed that, for a synchronously-rotating planet, persistent heating can lead to evolving convective motions, with (spherical harmonic) ‘degree-1 convection’, viz. a single upwelling and a single downwelling in opposite poles, perhaps developing over 1 Gyr.

*Ionising radiation:* radiation carrying sufficient energy to liberate electrons from atoms or molecules includes high-energy electromagnetic waves, as well as energetic subatomic particles, ions or atoms. Ionising radiation impinging on an atmosphere leads to energy deposition, extended ionospheres (which can modulate particle escape and modify atmospheric circulation), atmospheric erosion, ion drag and resistive heating (§11.4.5).

For close-in planets, the stellar wind can be particularly important for non- or only weakly-magnetised planets. Associated effects include stellar (super-)flares (§8.10.6), the production of energetic neutral atoms (§8.10.7), and coronal mass ejections (§8.10.6).

*Magnetic fields:* magnetic field interactions encompass a range of effects, with dependences both on the stellar magnetic field (§8.3.5), and the possible presence of a magnetic field in the planet itself. Interaction between the stellar and planetary magnetic fields also leads to enhanced X-ray (§8.10.4) and radio (§8.10.5) emission.

*Stellar activity:* intrinsic stellar activity acts as a noise source for most discovery and detection methods, considered separately under radial velocities (§2.4.5), astrometry (§3.3.4), and transits and eclipses (§6.11.1). In addition, there is some evidence that increased tidal and magnetic interactions enhance the host star’s chromospheric and coronal activity (§8.10.2).

The following sections describe interactions not covered elsewhere. There is considerable overlap between the various effects.

### 8.10.2 Magnetic and chromospheric activity

Exoplanet host stars display a variety of chromospheric and magnetic activity which is primarily dependent on the spectral type rather than on whether the star hosts planets or not. Such activity can be quantified statistically in terms of jitter in radial velocity (§2.4.5), astrometry (§3.3.4), and photometry (§6.11.1), as a function of spectral type and luminosity class.

Large-scale studies of chromospheric activity of relevance to exoplanet studies, and comparisons between stars with and without planets, include chromospheric activity and jitter for 2630 stars from the California planet search (Isaacson & Fischer, 2010); chromospheric activity for stars with and without planets (Canto Martins et al., 2011); chromospheric activity of 670 southern stars from the Magellan planet search programme (Arriagada, 2011); and trends of chromospheric activity with and without planets (Gonzalez, 2011).

**Enhanced activity** Observations indicate that some close-in hot Jupiters undergo episodes of periodic or enhanced stellar activity, most probably linked to the presence of the planet through magnetic or tidal interactions (§6.28.8). Effects are expected to be greatest in the outermost stellar layers, viz. in the chromosphere, transition region, and corona. The broad, deep photospheric absorption lines of Ca II H and K provide an important diagnostic, allowing chromospheric emission to be observed and monitored at the highest contrasts.

Progress in understanding this type of enhanced interaction-driven activity has built on studies of binary stars, which are known to be generally more active, for example in X-rays, than single stars of the same type and rotation rate (e.g. Zaqarashvili et al., 2002, and references), and where the effect has generally been attributed to tidal or magnetic interactions.



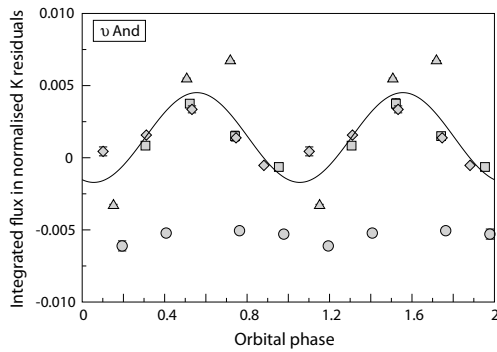


Figure 8.32: Integrated flux of the Ca II K line residuals from a normalised mean spectrum of  $\nu$  And as a function of orbital phase. Data were acquired in 2001 Aug (circles), 2002 Jul (squares), 2002 Aug (triangles), and 2003 Sep (diamonds). The solid line is the best-fit hot-spot model fitted to the 2002 and 2003 data. The Ca II emission is  $169^\circ$  out of phase with the sub-planetary point. From Shkolnik et al. (2005, Figure 8), by permission of IOP Publishing/AAS.

**Energy dissipation** Tidal or magnetic interactions would be expected to display different periodicities with respect to the planet’s orbital rotation (Cuntz et al., 2000). Tidal interactions should result in two tidal bulges on the star, and an enhanced activity which should be modulated at half the planet’s orbital period. For energy released via reconnection during interaction between the planetary magnetosphere and the stellar magnetic field, the effect should be modulated at the planet’s orbital period. Saar et al. (2004) estimated the associated energy release

$$E \propto B_\star B_p \nu_{\text{rel}} a_p^{-n} \propto a_p^{-n}, \quad (8.31)$$

where  $B_\star$  and  $B_p$  are the stellar and planetary magnetic fields,  $\nu_{\text{rel}}$  is the relative velocity between them which produces the shear in the magnetic fields leading to reconnection. They gave  $n = 3$  very close to the star and  $n = 2$  farther away.

**Observations** Given that tidal and magnetic effects are expected to depend strongly on the star–planet separation, observations have been focused on planets with the smallest semi-major axes. Periodic activity has been reported in Ca II H and K and/or Balmer line emission in the case of HD 179949 (Shkolnik et al., 2003; Scandariato et al., 2013) and  $\nu$  And (Shkolnik et al., 2005). It has also been inferred from optical brightness variations in the case of  $\tau$  Boo (Walker et al., 2008).

In these cases, activity is modulated at the stellar rotation rate, suggesting magnetically-driven interactions, while the location of maximum chromospheric heating is found to be phase shifted with respect to orbital conjunction (Shkolnik et al., 2005), leading the sub-planetary point by typically  $60 - 70^\circ$ , and up to  $170^\circ$  in the case of  $\nu$  And (Figure 8.32). Activity may be intermittent over the longer term (Shkolnik et al., 2008).

In the case of CoRoT-7, a maximum entropy spot model of the light curve identifies three active regions at three discrete longitudes that appear to migrate at different rates, probably as a consequence of surface differential rotation (Lanza et al., 2010).

**Stellar magnetic fields** The stellar magnetic field is inferred to play a key role in these interactions, either by triggering activity directly, or by tracing it indirectly, perhaps through tidal interactions influencing the magnetic field by enhancing the shear at the base of the convective envelope (§8.3.5).

In addition to the use of proxies for probing stellar magnetic properties, such as the rotational modulation of magnetic features (star spots and faculae) on the stellar surface (§8.3.1), more quantitative diagnostics are provided by Zeeman–Doppler imaging exploiting spectropolarimetry.<sup>2</sup> A spectropolarimetric snapshot survey, BCool, is being conducted on some 30 solar-type planet-hosting stars, providing candidates for more detailed Zeeman–Doppler imaging (Mengel et al., 2017).

Magnetic fields and activity cycles are detected in a few host stars, e.g.  $\iota$  Hor (Metcalf et al., 2010; Flores et al., 2017); HD 46375 (Gaulme et al., 2010a); HD 70642 and HD 154088 (Fossati et al., 2013b);  $\epsilon$  Eri (Metcalf et al., 2013), and  $\tau$  Boo (Butler et al., 2006b; Catala et al., 2007; Donati et al., 2008; Fares et al., 2009, 2013).

The phase lag between orbital conjunction and epochs of enhanced activity observed for HD 179949 and  $\nu$  And has been attributed to an offset between the magnetic and rotation axes (McIvor et al., 2006), to the propagation of Alfvén waves (Preusse et al., 2006), or to other magnetic field configurations (Lanza, 2008).

**$\tau$  Boo** The case of  $\tau$  Boo has been well characterised. A  $4.1 M_J$  planet orbits the F7 star with  $P = 3.31$  d and  $a = 0.048$  au (Butler et al., 2006b). The star has a moderate-intrinsic activity, and a relatively shallow convective envelope of about  $0.5 M_J$  (Shkolnik et al., 2005, 2008). It has a weak magnetic field, determined by Zeeman–Doppler imaging, of  $1 - 3 \times 10^{-4}$  T (Catala et al., 2007), which underwent a global magnetic polarity reversal between 2006–07 (Donati et al., 2008), and again between 2007–08 (Fares et al., 2009), with switches between a predominantly poloidal and a dominantly toroidal nature at different epochs. The observations suggest a magnetic (reversal) cycle of  $\sim 2$  yr, much shorter than the Sun’s, at 22 yr. Further observations have confirmed the polarity reversal, and the underlying 2-yr cycle period (Fares et al., 2013). The star has strong differential rotation

<sup>2</sup> Of various related tomographic techniques, *Zeeman–Doppler imaging* can be used to reconstruct a magnetic field map of a stellar surface. It is derived from an inversion of a time series (over many days) of the Stokes V profiles to provide a map of the magnetic topology, i.e. both the location of magnetic spots and the orientation of the field lines (e.g. Donati & Brown, 1997; Donati et al., 2006). Of planet-hosting stars, it has been applied to  $\tau$  Boo, yielding a weak magnetic field of 5–10 G and a magnetic (reversal) cycle of  $\sim 2$  yr (Fares et al., 2009), and to HD 46375, yielding magnetic field of  $\sim 5$  G (Gaulme et al., 2010a).

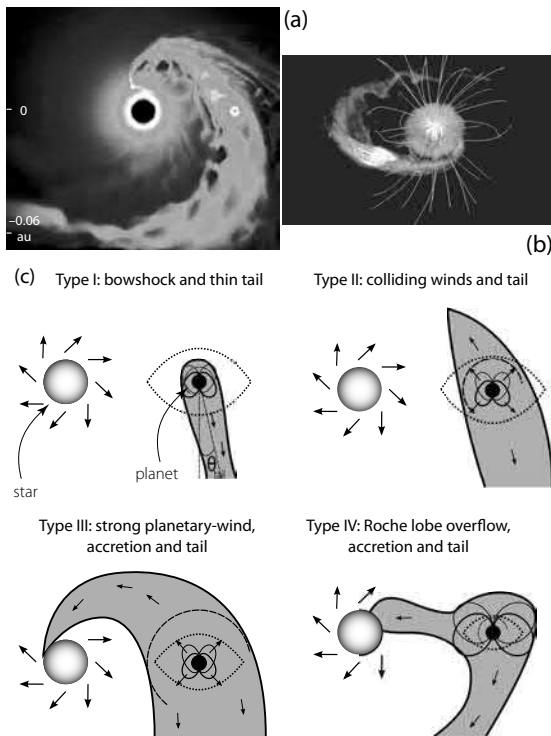


Figure 8.33: 3d magnetohydrodynamic simulations of close-in star–planet interactions, incorporating a star, a hot Jupiter at  $a = 0.05$  au, and realistic star and planetary plasma outflows controlled by their respective magnetic fields. For their model FvRb, (a) shows the logarithmic particle density, and (b) a 3d representation of the density structure and magnetic field lines. (c) Schematic of four classes of star–planet interactions, showing face-on views in the orbital plane of the four distinct morphological structures as they appear in the planet frame; shaded areas show material that flowed out of the planet, arrows indicate gas motions, and the closed loops sketch the planetary magnetosphere. Solid circular arcs in I and IV are of radius  $R_m$ , the distance where the magnetospheric pressure equals the total ambient pressure. Dashed circular arcs in II and III are the distance  $R_w$  where the ambient pressure equals the ram pressure of the planetary wind. The dotted line indicates the contour of the effective (gravity plus centrifugal) potential that crosses the Lagrange point  $L_1$ , at distance  $R_t$  from the planet. The classification scheme is based on the relative ordering of  $R_m$ ,  $R_w$ , and  $R_t$ . From Matsakos et al. (2015, Figs 9, 10, 13), reproduced with permission © ESO.

which does not change with the magnetic cycle: the equator rotates in 3 d, while its pole rotates in 3.9 d. This means that at latitude  $\sim 40^\circ$ , its rotation is synchronised with the orbital period of the planet. Fares et al. (2009) hypothesised that the short magnetic cycle may be the result of the star’s shallow convection zone, or it may be connected to the close-orbiting planet, for example by tidally synchronising the outer convective envelope, and thereby enhancing the shear at the tachocline.

**Planetary magnetic fields** Evidence for planetary magnetic fields is discussed in Section 8.10.5.

### 8.10.3 Stellar winds

Planets in close orbits interact with the magnetised wind of their host star. This magnetic interaction is a candidate for the enhanced chromospheric emissions seen in some systems, and also participates, along with tidal torques, in setting the migration time scale of the close-in planet. The nature of the interaction depends on the magnetic properties of the host star and of the planet, and on the overall magnetic topology.

As an example from a wide range of studies, Matsakos et al. (2015) used 3d magnetohydrodynamic simulations to suggest that these interactions could be classified into four general types, based on the relative magnitudes of three characteristic length scales that quantify the effects of the planetary magnetic field, the planetary outflow, and the stellar gravitational field in the interaction region (Figure 8.33). The flow structures they give rise to include bow shocks, cometary-type tails, and in-spiraling accretion streams.

Others have developed similar models of hot Jupiter systems to compute simulation grids for various properties of the orbiting planet, including their effects on atmospheric ionisation, coronal or chromospheric activity, or predictions of X-ray or radio emission (Koskinen et al., 2010a; Johansson et al., 2011a,b; Poppenhaeger & Schmitt, 2011b; Heyner et al., 2012; Krejčová & Budaj, 2012; Laine & Lin, 2012; Lanza, 2012; Kislyakova et al., 2013; Lanza, 2013; Shkolnik, 2013; Koskinen et al., 2014b; Lanza, 2014; Owen & Adams, 2014; Kislyakova et al., 2015; Miller et al., 2015; Alvarado-Gómez et al., 2016b; Nichols & Milan, 2016; Shaikhislamov et al., 2016; Staff et al., 2016; Strugarek, 2016; Tilley et al., 2016; Carroll-Nellenback et al., 2017; Erkaev et al., 2017).

**Orbit evolution** Planet orbits evolve with time due to tidal interactions, stellar mass losses, friction and gravitational drag forces, mass accretion, and evaporation onto or by the planet. Stellar rotation modifies the structure of the star and therefore the way these different processes occur. Changes in orbits, subsequently, have an impact on the rotation of the star.

Models are being developed that aim to account in a consistent way for interactions between the orbital evolution of the planet and the evolution of the rotation of the star (e.g. Privitera et al., 2016b,c). Privitera et al. (2016c) followed these through to engulfment showing, for example, that the surface velocities reached at the end of the orbital decay due to tidal forces and planet engulfment can be similar to values observed for fast rotating red giants. Engulfment is expected to increase the rotation rate of their convective envelope, which could lead to strong dynamo-triggered field, suggesting that high surface magnetic fields in red giants may be a signature of planet engulfment (Privitera et al., 2016a).

### 8.10.4 X-ray emission

Various effects related to the X-ray and ultraviolet irradiation of a close-in planet by the host star have been considered, in addition to atmospheric heating.

**Stellar X-ray and extreme ultraviolet emission** The majority of the X-ray and extreme ultraviolet luminosity of a star is emitted from the hot ( $\sim 1$  keV) corona. Coronal heating is related to the star’s magnetic activity, itself derived from dynamo mechanisms in its interior (e.g. Erdélyi & Ballai, 2007), and whose efficiency is determined by the interaction between convection in the outer envelope and differential rotation (e.g. Landstreet, 1992; Covas et al., 2005; Donati & Landstreet, 2009). Skumanich (1972) observed a proportionality between average surface magnetic field and stellar rotation, and suggested a dependence of activity on rotation due to the dynamo mechanism. Numerous studies have subsequently focused on the relationship between X-ray emission and rotation (e.g. Pallavicini et al., 1981; Randich et al., 1996; Pizzolato et al., 2003).

Stellar rotation slows with time as a result of magnetic braking (e.g. Ivanova & Taam, 2003, see also §8.2.6). For young stars with rotation periods less than 1–2 d the X-ray luminosity is saturated (e.g. Pizzolato et al., 2003; Micela et al., 1985), after which decreasing rotation leads to decreasing dynamo action, and hence to a decreasing X-ray luminosity with time (e.g. Pizzolato et al., 2003).

**Exoplanet evaporation** For close-in planets, the absorption of X-ray and extreme ultraviolet radiation by the planet’s atmosphere, leads to irradiation-driven mass loss. Early estimates of such mass loss were made, for example, for HD 209458 b (Vidal-Madjar et al., 2003) and HD 189733 b (Lecavelier des Etangs et al., 2010). The subject is also considered in the wider context of atmospheric loss in Section 11.4.5.

A simple model of exoplanet evaporation, mediated by X-ray/EUV heating, was developed by Lecavelier des Etangs (2007). Applied to known exoplanets, he found that they should not be losing significant mass at present irradiation levels. Given that irradiation would be much higher around a younger solar-type star, Penz et al. (2008) showed that evaporation can significantly affect the mass distribution of close-orbiting exoplanets.

**Detailed models** Progressively detailed modeling has allowed improved estimates of the evaporation history of transiting planets (Lecavelier des Etangs, 2007; Lammer et al., 2009b; Davis & Wheatley, 2009; Sanz-Forcada et al., 2010; Jackson et al., 2012a). Jackson et al. (2012a) used their improved X-ray emission–age relation to investigate the evaporation history of 121 transiting planets using an energy-limited model of evaporation, and accounting for Roche lobe effects (Erkaev et al., 2007). They estimated that 10–30% have lost more than 5% of their mass since formation, that the major loss occurred within the first Gyr, and that the most significant changes occurred in the first 100–200 Myr, i.e. during the ‘saturated phase’ of the host star. They also estimated the minimum formation mass for which a planet could be expected to have survived to an age of 4 Gyr for a range of stellar spectral types, orbital distances, initial planet densities, and evaporation efficiencies.

A possible correlation between planet mass versus orbital period had already been noted by Mazeh et al. (2005), and be-

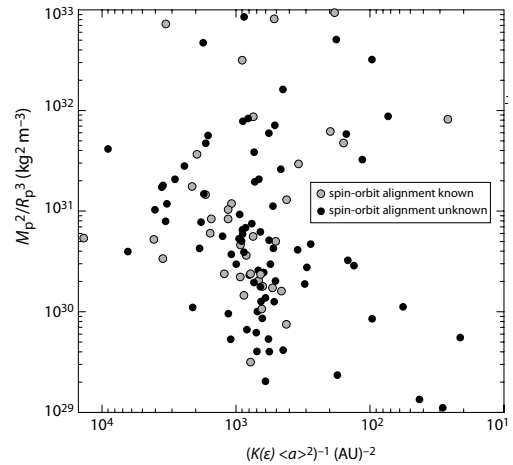


Figure 8.34:  $M_p^2/R_p^3$  versus  $(\langle a \rangle^2)^{-1}$  for 121 transiting exoplanets. The factor  $K(\epsilon)$  accounts for Roche lobe effects. Symbols indicate a known (light shaded) or unknown (black) misalignment between the planet orbit and the stellar rotation axis. From Jackson et al. (2012a, Figure 11), © Oxford University Press.

tween surface gravity and orbital period by Southworth et al. (2007) respectively. Both have been revisited as more planets have been discovered (e.g. Hansen & Barman, 2007; Pollacco et al., 2008; Davis & Wheatley, 2009). Jackson et al. (2012a) showed that a linear cut-off in the  $M_p^2/R_p^3$  versus  $(a_p)^{-2}$  plane is an expected outcome of thermal evaporation (Figure 8.34).

A constraint on planet migration can also be inferred from the lack of dependency on the spin–orbit misalignment angles evident in (the colour-coded original of) Figure 8.34. If aligned systems represent those which underwent disk-based migration, and misaligned systems are those which underwent non-disk-based migration, their similar dependency implies that non-disk-based migration also happens early in the life of a planetary system, i.e. within the first 100 Myr.

Of other individual studies, Lalitha et al. (2014) used XMM–Newton observations of the transiting super-Earth GJ 1214 b, and more recent models of mass loss, to derive  $L_X = 7.4 \times 10^{18} \text{ J s}^{-1}$ , a coronal temperature of  $3.5 \times 10^6 \text{ K}$ , and an evaporation rate of  $1.3 \times 10^7 \text{ kg s}^{-1}$ , implying that it has lost a total mass of  $\sim 2 - 5.6 M_\oplus$ .

**Stars with and without planets** A systematic study of X-ray emission from the host stars of Doppler-detected planets, also aiming at understanding their coronal activity and possible star–planet interactions, was made by Kashyap et al. (2008). They searched for X-ray counterparts in archival data from ASCA, EXOSAT, Einstein, ROSAT, XMM–Newton and Chandra, complemented by dedicated XMM–Newton targeted surveys. Out of some 230 host stars, 70 were detected serendipitously or in pointed observations. As a whole, main sequence stars with giant planets were found to be broadly similar in X-ray characteristics to the field star sample.

For close-in giant planets with small star–planet separations,  $a_p$ , tidal or magnetic interactions may nevertheless result in enhanced X-ray activity. In the model of

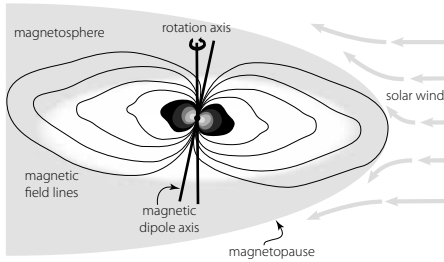


Figure 8.35: Schematic of the interaction between the solar wind, and the magnetosphere of a planet with a significant magnetic dipole moment. An offset between the dipole and rotation axes leads to rotational modulation of the radio cyclotron emission, analogous to that seen in radio pulsars.

Cohen et al. (2009), a close-in planetary magnetosphere restricts the expansion of the stellar magnetic field and the acceleration of the stellar wind, causing a higher plasma density in a coronal hot spot. They found variations of the X-ray flux of  $\sim 30\%$  as the hot spot rotates in and out of view, and to an overall X-ray flux enhanced by  $\sim 1.5$  for a stellar dipole field, and by  $\sim 15$  for a Sun-like magnetic field at maximum activity.

After accounting for their sample biases, Kashyap et al. (2008) reported a possible difference between the X-ray properties of host stars with  $a_p < 0.15$  au,  $\langle L_X \rangle = 10^{28.49 \pm 0.09} \text{ erg s}^{-1}$ , and those with larger separations  $a_p > 1.5$  au,  $\langle L_X \rangle = 10^{27.85 \pm 0.18} \text{ erg s}^{-1}$ , suggesting that stars with close-in giant planets may indeed be more active compared with those with larger separations.

Poppenhaeger et al. (2010) subsequently investigated the X-ray activity of 72 planet hosts within 30 pc known at the end of 2009, using ROSAT and XMM-Newton data, but found no significant correlation of X-ray luminosity with  $M_p$  or  $a_p$ . They concluded that while coronal star–planet interactions are evidently important for a few individual targets, they do not result in a major effect on planet-hosting stars in general. Observed correlations were attributed to selection effects by Poppenhaeger & Schmitt (2011a).

As suggested by the magnetohydrodynamic model of Cohen et al. (2010), significant star–planet interactions require not only that the star–planet separation be small, but that the Alfvén surfaces of the stellar and planetary magnetospheres must also be interacting. For close-in planets, positive correlation between stellar X-ray luminosity and  $M_p$  has been attributed to star–planet magnetic field interaction, with an increase of  $\times 8$  between  $1 - 10 M_J$  (Scharf, 2010).

The MUSCLES survey, to establish the spectral energy distributions of a number of planet-hosting stars, is based around ultraviolet observations with HST (France et al., 2016; Youngblood et al., 2016; Loyd et al., 2016).

**Orbital torques** If the momentum flux from the evaporative wind is not aligned with the planet/star axis, it exerts a torque on the planet's orbit (Teyssandier et al., 2015). The wind causes the planet to drift outwards if atmospheric circulation is prograde (superrotating) and *vice versa*. A close-in super-Earth that loses a large fraction of its mass in a wind could drift a few percent of its semi-major axis, an effect placing constraints on the evolution of resonant pairs such as Kepler-36 b/c.

**Signatures of tidal disruption** X-ray signatures have been attributed to tidal disruption events (§6.14.21), including a giant X-ray flare in NGC 5905 (Li et al., 2002), and hard X-rays in NGC 6388 (Del Santo et al., 2014).

**Modulation during transits** Effects related to the modulation of X-ray intensity during transits is considered in Section 6.16.1.

### 8.10.5 Radio emission

There are two routes to the possible detection of exoplanets at radio wavelengths, neither of which has yet yielded positive results. The first exploits radio emission generated by certain stars, independently of the presence of a planet. An orbiting planet would, however, induce a time-varying displacement of the radio emission as the star orbits the barycentre. Analogous to detection by optical astrometry, it is described in Section 3.11.1.

The second, the subject of this section, targets the direct detection of emission arising from magnetospheric interaction with their host stellar wind, as observed for the radio-emitting planets in the solar system (box, page 426). Somewhat analogous to direct optical imaging, it is facilitated by the typical absence of significant non-thermal radio emission from the closely-separated host star.

**Radio Bode's law** For the solar system planets which are known radio emitters (box, page 426), various forms of an empirical scaling law, the *radio Bode's law*, have been constructed from the observed relation between their average radio power and the incident kinetic power due to the solar-wind ram pressure on their magnetospheric cross sectional area (Desch & Kaiser, 1984; Zarka, 1992). For example, Zarka et al. (2001, eqn 1) gives

$$P_{\text{radio}} \propto \left( \frac{N_0}{a^2} \right) V_w R_{\text{mp}}, \quad (8.32)$$

where  $N_0$  is the average stellar wind density at 1 au,  $a$  is the planet–star separation,  $V_w$  is the solar wind speed, and  $R_{\text{mp}}$  is the day-side magnetopause distance. An alternative form is (Farrell et al., 2004a, eqn 1)

$$P_{\text{radio}} = 4 \times 10^{11} W \left( \frac{\omega}{10 \text{ hr}} \right)^{0.79} \left( \frac{M_p}{M_J} \right)^{1.33} \left( \frac{a}{5 \text{ au}} \right)^{-1.6}, \quad (8.33)$$

where  $\omega$  is the planet rotation period, and where  $\omega$  and  $M$  are proxies for the planetary magnetic moment.

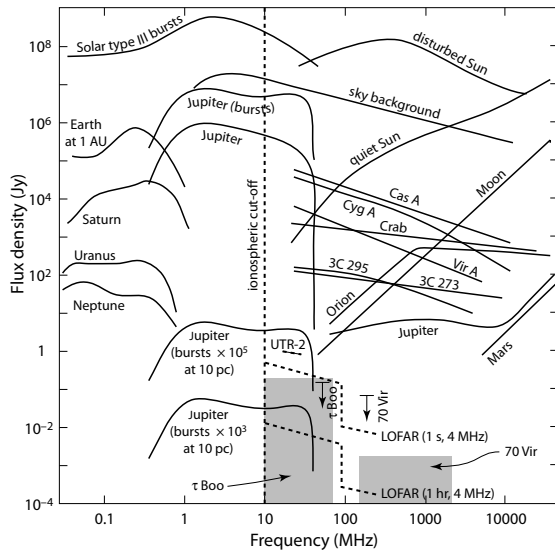


Figure 8.36: Flux versus wavelength for astronomical radio sources ( $1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ ). Galactic, extragalactic and solar spectra are from Kraus (1966, Figure 8.6a). Planetary spectra corresponding to auroral emission are from Zarka (1992). Shaded boxes are predictions for  $\tau$  Boo and 70 Vir from Farrell et al. (2004b), with corresponding illustrative upper limits from recent observations. The Earth's ionospheric cut-off is shown at 10 MHz. Adapted from Zarka (2004, Figure 1).

**Application to exoplanets** By analogy with the solar system planets, radio emission should accompany extrasolar planets which possess dynamo-driven magnetic fields combined with a source of energetic magnetospheric electrons. The latter may arise from auroral processes, or from magnetic planet-satellite coupling. Detection of exoplanet radio emission would provide information on its magnetic field strength, rotation period, and perhaps the presence of exomoons. Polarisation may be a further diagnostic.

In the context of the development of life, and analogous with the situation on Earth, magnetic fields may be important in providing protection from the energetic particles arising from stellar winds, stellar flares, and cosmic rays. Accordingly, the presence of radio emission may be one possible proxy for habitability.

**Magnetic fields: theory** The existence of intrinsic magnetic fields in giant exoplanets (and brown dwarfs) is expected from models of their internal structure (see also §9.6.4). These models predict the existence of an internal energy source driving convection (which increases with mass, and decreases with time as the planet cools), and the existence of an electrically-conducting liquid-hydrogen metallic layer formed by the dissociation and ionisation of molecular  $\text{H}_2$  under extreme pressure (e.g. Burrows et al., 1997; Hubbard et al., 2002).

Sánchez-Lavega (2004) derived estimates of the magnetic field and dipole moment as a function of exoplanet mass, age, and rotation rate, for masses in the range  $0.3 - 10 M_J$ , and with rotation periods ranging from tidal synchronism (1–4 d) to centrifugal breakup (2–3 h). Based on the heat generation given

by the evolutionary models of Burrows et al. (1997), Sánchez-Lavega (2004) showed that convective motions develop in the metallic region, and derived estimates of the resulting magnetic field strengths from relevant scaling laws.

The conclusion is that strong fields,  $30 - 60 \times 10^{-4} \text{ T}$ , are likely in young, massive, rapidly rotating planets, falling to  $\sim 10^{-4} \text{ T}$  for older or spin-orbit synchronised planets (Figure 8.37). A similar law with corresponding predictions is given by Christensen et al. (2009a).

Other models are clarifying their formation and lifetimes, their role in planetary protection, and their coupling with the stellar magnetic field (Christensen et al., 2009b; Reiners & Christensen, 2010; Driscoll & Olson, 2011; Tachinami et al., 2011; Zuluaga & Cuartas, 2012; Kuzmychov & Berdyugina, 2013; Saur et al., 2013; Vilim et al., 2013; Zuluaga et al., 2013; Strugarek et al., 2014; Yadav & Thorngren, 2017).

**Magnetic fields: evidence** Little direct evidence or information is available on exoplanet magnetic fields. Indirect evidence for their existence includes the modulation of activity indicators of their host stars (such as Ca emission-line intensity or X-ray activity) phased with the planetary orbits. Such variations have been attributed to magnetic reconnection between the stellar and planetary fields (Cuntz et al., 2000; Cuntz & Shkolnik, 2002; Preusse et al., 2006; Lanza, 2008, 2009). Specific studies have been reported in a number of cases, including HD 179949 (Shkolnik et al., 2003, 2005; McIvor et al., 2006; Lanza, 2008; Saar et al., 2008) and  $\nu$  And (Shkolnik et al., 2005; Lanza, 2008).

Combining archival and targeted surveys, Kashyap et al. (2008) found that out of the 230 stars then identified with planets, roughly one-third were detected in X-rays, with stars accompanied by close-in giants being on average more X-ray active by a factor four than those with more distant planets. This has also been taken to suggest that giant planets in close proximity to their host stars influence the stellar magnetic activity.

Early ingress in the ultraviolet transit light curve for the highly-irradiated planet WASP-12 b (§6.14; Fossati et al., 2010b) has been attributed to a magnetospheric bow shock (Vidotto et al., 2010). This could also provide constraints on the planetary magnetic field strength.

**Radio flux predictions** For radio emission originating from a stellar wind incident on the planetary magnetosphere, expressions for the expected radio flux,  $P_{\text{radio}}$ , have been formulated in terms of the conditions at the planet (Zarka et al., 2001; Lazio et al., 2004a; Stevens, 2005; Grießmeier et al., 2005a; Zarka & Halbwachs, 2006; Grießmeier et al., 2007a,b; Zarka, 2007; Jardine & Collier Cameron, 2008; Hess & Zarka, 2011; Nichols, 2011). Thus George & Stevens (2007, eqn 1) suggest the form

$$P_{\text{radio}} \propto \dot{M}_{\star}^{2/3} V_w^{5/3} \mu_p^{2/3} a^{-4/3} d^{-2}, \quad (8.34)$$

where  $\dot{M}_{\star}$  is the stellar mass-loss rate,  $V_w$  is the stellar wind speed at the magnetosphere,  $\mu_p$  is the planetary magnetic moment,  $a$  is the planet-star separation, and  $d$  is the stellar distance.

Specific dependencies can then be invoked to establish predicted radio fluxes tied to particular observables. Thus the stellar mass-loss rate is related to the stellar X-ray luminosity (Wood et al., 2002; Cranmer, 2008). The planetary magnetic moment is likely to scale

**Radio emission in the solar system:** Of the various sources of radio emission in the solar system (Kraus, 1966, Chapter 8), Jupiter was first detected at radio wavelengths using the Mills Cross antenna at 22.2 MHz (Burke & Franklin, 1955). It has since been known as a bright and variable source at decametric wavelengths (3–40 MHz).

Five of the solar system planets with a dynamo-driven magnetic field are known to produce non-thermal low-frequency ‘auroral’ radio emission as a result of interaction between the solar wind and their planetary *magnetospheres*, viz. the cavity created in the flow of the solar wind by the planet’s internally generated magnetic field (Figure 8.35): Earth, Jupiter, Saturn, Uranus and Neptune. Additional intense radio bursts arise from electrodynamic interactions between Jupiter and its satellite Io, referred to as the ‘Jupiter–Io flux tube’ (Zarka et al., 2001; Hess et al., 2008).

Radio emission from the giant planets other than Jupiter falls off below the Earth’s ionospheric cut-off at ~10 MHz (Figure 8.36). Their magnetospheres were instead directly detected by the fly-by missions: first by Pioneer 10 for Jupiter in 1973, by Pioneer 11 for Saturn in 1979, and by Voyager 2 for Uranus in 1986 (Ness et al., 1986) and Neptune in 1989 (Ness et al., 1989). Cassini, the fourth probe to visit Saturn, and the first to enter orbit around it, made *in situ* radio measurements between 2004–17 (e.g. Wang et al., 2010; Kurth et al., 2016).

Magnetic fields of the giant planets are generated by dynamo processes arising from convective motions in the electrically-conducting metallic hydrogen circulating in their outer cores (Connerney, 1993; Guillot et al., 2004). The solar system planetary dynamos are nevertheless highly diverse, with Uranus and Neptune having displaced and tilted fields (Appendix A, Table A2), with quadrupole components, and magnetic field lines distorted by orbiting satellites (Russell, 1993). Detailed models involve non-linear chaotic processes, which are difficult to solve numerically even for the solar system giants with their abundance of observational data (Stevenson, 2003; Badman et al., 2015; Grodent, 2015).

Although other effects contribute (e.g. Blanc et al., 2005; Zarka & Kurth, 2005), the dominant mechanism for low-frequency radio waves from the solar system planets is cyclotron maser emission from energetic (keV) electrons interacting with the planetary magnetic field. Characteristic frequencies are determined by the magnetic field strength, with a sharp cut-off above ~40 MHz in the case of Jupiter. Radio emission is not isotropic, but emitted over a certain solid angle, some 1.6 sr in the case of Jupiter (Zarka et al., 2004). Intensities are furthermore time varying, modulated by solar coronal mass ejections, planetary rotation, and satellite interactions (Higgins et al., 1997; Gurnett et al., 2002). At higher (GHz) frequencies, lower-level synchrotron emission dominates.

with the planetary mass. In the solar system the relationship, known as Blackett’s law (Blackett, 1947), is variously given as  $\mu_p \propto M_p$ , or  $\mu_p \propto \omega M_p^{5/3}$ , where  $\mu_p$  is the planetary magnetic moment,  $M_p$  the planetary mass, and  $\omega$  the planetary angular rotation frequency.

Lazio et al. (2004a) estimated that most of the known extrasolar planets should emit in the frequency range 10–1000 MHz with flux densities of order 1 mJy. Magnetised hot Jupiters might emit radio emission several orders of magnitude stronger than Jovian levels (Zarka et al., 2001). Stevens (2005) compiled a potential target list, and estimated that  $\tau$  Boo, GJ 86,  $\nu$  And, HD 1237, and HD 179949 are the most promising, with peak frequencies in the range 8–48 MHz.  $\tau$  Boo is also predicted to be the strongest emitter in the 10–100 MHz band by Reiners & Christensen (2010), followed by  $\nu$  And, GJ 86, GJ 3021, and HD 189733. For nearby stars with surface field strengths above  $10^{-4}$ – $10^{-3}$  T, Jardine & Collier Cameron (2008) predicted radio fluxes of tens of mJy for exoplanets close to their host stars.

Close-in planets with short orbital periods may have more complex magnetospheric geometries and interactions (e.g. Ip et al., 2004; Nichols, 2012). Nichols (2012) considered the magnetosphere–ionosphere coupling at Jupiter-like exoplanets with internal plasma sources such as volcanic moons, identifying 91 potential targets within 25 pc, most favourably  $\epsilon$  Eri and HIP 85523.

But tidal locking may modify the planetary dynamo, perhaps resulting in a weaker magnetic field and a smaller magnetic moment (Gri fmeier et al., 2004).

**Survey instruments and searches** Even before detection of the first exoplanets, a number of radio searches had been conducted. Yantis et al. (1977) reported a search for Jovian-like exoplanets using the Clark Lake Radio Observatory at 26.3 MHz, aiming to distinguish planetary bursts from stellar bursts by the presence of a high-frequency cut-off, and possibly modulation associated with planetary rotation. Winglee et al. (1986) used the VLA at 1.4 and 0.33 GHz to search six nearby stars.

Later low-frequency surveys, some having been applied to exoplanet searches, include the Cambridge 6C (151 MHz, Hales et al., 1993), 7C (151 MHz, Riley et al., 1999) and 8C (38 MHz, Hales et al., 1995), the Ukrainian UTR–2 (Braude et al., 2006), the VLA Low-Frequency Sky Survey, VLSS (74 MHz, Lane et al., 2008), the Giant Meterwave Radio Telescope, GMRT (Ananthakrishnan, 1995; Sirothia et al., 2014), and the Murchison Widefield Array (80–300 MHz, Murphy et al., 2015).

China’s Five-hundred-meter Aperture Spherical radio Telescope (FAST), completed in 2016, is the most sensitive single-dish telescope in the low-frequency bands 70 MHz–3 GHz, and is part of China’s contribution to the SKA (Nan et al., 2011; Li & Pan, 2016). Planet searches are planned (Li et al., 2013).

The Low-Frequency Array, LOFAR (van Haarlem et al., 2013), operates over 10–240 MHz ( $\lambda = 30$ –1.2 m), with design sensitivity of 2 mJy in a 15 min integration. It was officially opened, in incomplete form, in June 2010, with regular observations starting in December 2012, and is still expanding. The final configuration foresees up to 10 000 dipole antennae sited in NL, D, S, UK, and F, with baselines up to 1500 km. Its sensitivity and wide field will advance the search for exoplanet radio emission (Cairns, 2004; Farrell et al., 2004b; Zarka, 2004).

Beyond LOFAR is the 12-country Square Kilometer Array, SKA (e.g. Heyl, 2011a,b; Mehrabi & Rahvar, 2013), with its own precursors: the Australian SKA Pathfinder (ASKAP), the Murchison Widefield Array (MWA), and the S. African 64-antenna MeerKAT (and its operational 7-dish testbed, KAT-7). As of the

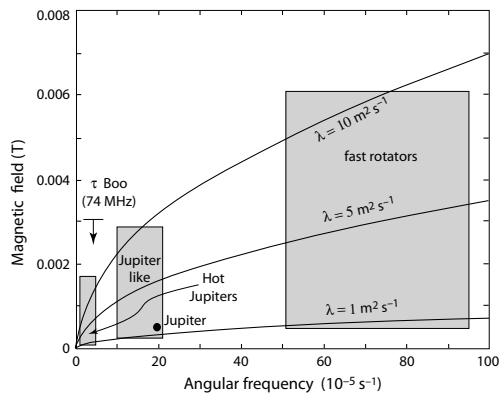


Figure 8.37: Predicted magnetic field intensity in giant exoplanets, at the top of the metallic-hydrogen layer, as a function of angular rotation frequency, for three values of the magnetic diffusivity,  $\lambda$  (Nellis, 2000). Boxes delineate plausible values for the magnetic field for three rotation periods: hot Jupiters (periods of 1–4 d, assuming spin–orbit synchronisation), Jupiter-like planets (periods of 10–20 h), and fast rotators (periods of 2–3 h). The surface value for Jupiter is indicated. The upper limit for  $\tau$  Boo b was derived from radio observations at 74 MHz (Lazio & Farrell, 2007). From Sánchez-Lavega (2004, Figure 1), by permission of IOP Publishing/AAS.

end of 2017, construction is scheduled to begin in 2018 for initial observations by 2020. Applications to exoplanets and SETI have been considered (Tarter, 2004; Lazio et al., 2004b; Lazio, 2008), along with prospects for imaging protoplanetary disks (Wilner, 2004), and detecting exoplanet magnetospheric radio emission (Zarka et al., 2015).

**Upper limits and possible detections** Since the first exoplanet discoveries, radio detections have been attempted with various telescopes, and at different (but mostly low) frequencies. Although there are many uncertainties in predicting which are likely to be the strongest emitters, searches have focused on the short-period planets, but with observations of wider orbital separations also being pursued.

Reported work, without detections unless otherwise indicated, includes (chronologically): use of the VLA targeting seven exoplanets at 1.4 GHz, 0.33 GHz, and 74 MHz, reaching 50 mJy at the lowest frequencies (Bastian et al., 2000); use of the Green Bank 100 m at 330 MHz to survey 20 exoplanets (Langston et al., 2002); use of the UTR–2 to survey 20 exoplanets at 10–25 MHz down to 1.6 Jy (Ryabov et al., 2003); use of the VLA at 74 MHz to observe  $\tau$  Boo, with upper limits 135–300 mJy (Lazio & Farrell, 2007); use of the GMRT at 150 MHz to observe the short-period exoplanets  $\tau$  Boo, 70 Vir,  $\nu$  And, GJ 876, HD 162020, HD 179949 (Majid et al., 2006), and the longer-period exoplanets  $\epsilon$  Eri and HD 128311, with upper limits in the range 3–6 mJy (George & Stevens, 2007); use of the VLA at 325 and 1425 MHz to observe HD 80606 (Lazio et al., 2010b); use of the VLA at 74 MHz in a blind search around nearby stars (Lazio et al., 2010a); use of the WSRT at 1.7 GHz with an upper limit of 0.13 mJy, some two orders of magnitude below that expected from its rotational velocity (Stroe et al., 2012); and use of the Murchison Widefield Array at 154 MHz to observe 17 mostly radial velocity hosts with

upper limits of 15–100 mJy (Murphy et al., 2015).

The bright, nearby hot-Jupiter transiting system HD 189733 has been observed with GMRT at 244 and 614 MHz, with upper limits of 2 mJy and 160  $\mu$ Jy respectively (Lecavelier des Etangs et al., 2009), and at 150 MHz with an upper limit of 2.1 mJy (Lecavelier des Etangs et al., 2011). It has also been observed at 327–347 MHz with the Green Bank telescope with an upper limit of 47 mJy (Smith et al., 2009a), and specifically during the period of secondary eclipse (Smith et al., 2009b).

HD 209458 was observed with GMRT at 150 MHz, prior to, during, and after secondary eclipse, to distinguish any background emission. Upper limits of 3.6 mJy were reported (Lecavelier des Etangs et al., 2011).

Possible (unconfirmed) detections from a 1 sr survey with GMRT and/or VLA NVSS/FIRST were reported by Sirothia et al. (2014) for four radial velocity discoveries (61 Vir, HD 43197, HD 86226, HD 164509), one transiting system (WASP–77A), and the direct imaging detection 1RXS J1609–21.

**Other sources of radio emission** These include:

*Magnetic white dwarfs:* electron–cyclotron radio emission from terrestrial planets in close orbits around magnetic white dwarfs may render them detectable (Willes & Wu, 2004, 2005).

*Stellar winds:* Katarzyński et al. (2016) estimated that radio emission produced by stellar winds (§8.10.3) could be detected by currently operating VLBI networks at  $\sim$ 1 GHz.

*Red giant phase:* radio emission due to interactions with a dense stellar wind may be particularly intense when stars evolve off the main sequence to the red-giant branch, becoming orders of magnitude more luminous, and losing mass at much higher rates. Planetary companions at separations of a few au would be heated to the level of canonical hot Jupiters, and also subjected to a dense stellar wind (Fujii et al., 2016).

*Lightning:* lightning is a transient phenomenon of several known cloudy atmospheres in the solar system, with manifestations in both the optical and radio (see Section 11.4.1).

### 8.10.6 Flares, super-flares and CMEs

**Flares** Solar flares result from the rapid loss of magnetic energy stored near sun spots, perhaps by magnetic reconnection, releasing  $10^{22}$ – $10^{25}$  J on time scales of hours (e.g. Allred et al., 2015; Janvier et al., 2015; Benz, 2017), and classified (A, B, C, M, X) according to X-ray flux. Coronal mass ejections (§8.10.6) often but not always accompany them (Yashiro et al., 2006). Forecast efforts are gaining some success (Bobra & Couvidat, 2015).

Analogous *stellar flares* have been observed on many stars (Schaefer, 1989), including many Kepler targets (e.g. Balona, 2012; Balona et al., 2016; Van Doorselaere et al., 2017). Flares are particularly prominent in M dwarfs (e.g. Segura et al., 2010; Tofflemire et al., 2012; Hawley et al., 2014; Yang et al., 2017b). Although there is general agreement on the underlying energy source, it is not clear how the magnetic energy is transformed into particle kinetic energy, nor how some particles are accelerated to the GeV range.

**Super-flares** Even larger *super-flares*, with energies  $10^{26}$ – $10^{31}$  J, durations of hours to days, and visible from X-ray to optical frequencies, have been seen on rapidly

rotating (Shibata & Yokoyama, 2002) as well as on otherwise normal F–G main sequence stars (Landini et al., 1986; Schaefer et al., 2000; Nogami et al., 2014). Even with the Kepler results, while certain correlations are evident, the detailed origin of super-flares remains uncertain (e.g. Wichmann et al., 2014; Maehara et al., 2017).

**Relevance to exoplanets** Rubenstein & Schaefer (2000) proposed that super-flares are caused by magnetic reconnection between fields of the star and a close-in Jovian planet with sufficient magnetic dipole strength, in analogy with the flaring seen in RS CVn binaries. The magnetic field lines connecting the pair will be wrapped by orbital motion, and interaction of field loops with the passing planet will initiate reconnection events. At the time of that study, only one super-flare star,  $\kappa$  Cet, had been the target of a specific planet search, and a Saturn-mass planet had not been excluded. None were discovered around the stars studied by Maehara et al. (2012), indicating that hot Jupiters associated with super-flares are rare.

Super-flares on the Sun, which would be catastrophic for life on Earth (see also §11.7.3), would not be expected in this model since there is no planet with a large magnetic dipole moment in a close orbit, although other possibilities exist (Shibata et al., 2013; Katsova et al., 2018).

For future atmospheric spectroscopy, temporal stellar (flux) disturbances may affect atmospheric chemical abundances, such as H and NH<sub>3</sub>, leading to variations in planetary spectra of up to 150 ppm if performed during transit, and with significant differences pre- and post-flare (Venot et al., 2016).

**Kepler contribution** Pre-Kepler, the small number of super-flares on solar-type stars hindered a detailed study. Analysis of 83 000 Kepler stars observed over 120 d led to the identification of 365 super-flares, including some from slowly rotating solar-type stars (Maehara et al., 2012; Shibayama et al., 2013; Wichmann et al., 2014; Savanov & Dmitrienko, 2015a). Stars with relatively slow rotation can produce flares as energetic as those of the more rapid rotators, although their average flare frequency is lower, with the total energy being related to the total coverage of the star spot (Notsu et al., 2013). Some support for the association with exoplanets was found for KIC–11764567, where hints of a periodic flare frequency cycle of 430–460 d is observed (Kitze et al., 2017). A moderate flare was observed on the planet host HD 189733 during primary transit (Klocová et al., 2017; Chadney et al., 2017). Flares from KIC–7341653 may be associated with a migrating long-lived photospheric spot or a faint solar mass companion (Makarov & Goldin, 2017).

The 2016 Kepler catalogue of stellar flares lists 851 168 candidate flares, from 4041 stars, or 1.9% of the stars in the Kepler database, with an average energy of  $\sim 10^{28}$  J (Davenport, 2016). Detections include Kepler–438, a habitable zone candidate with one of the highest Earth Similarity Index (§11.7.4).

FBEYE (Flares By-Eye) is an IDL super-flare detection and validation routine for the Kepler data (Johnson et al., 2017a).

**Stellar proton events** Solar protons normally have insufficient energy to penetrate Earth's magnetic field. *Solar proton events* (SPE), or *proton storms*, occur when particles (mostly protons) emitted by the Sun are accelerated either close to the Sun during a flare or in interplanetary space by coronal mass ejection shocks. The energetic protons can penetrate the Earth's magnetic field and cause ionisation in the ionosphere (an effect similar to auroral events, except that protons rather than electrons are involved), as well as a significant radiation hazard to spacecraft and astronauts. Analogous *stellar proton*

*events*, suggested by super-flares, may have significant implications for habitability (Atri, 2017).

**Coronal mass ejection** Coronal mass ejections (CME) are events with a significant release of plasma and magnetic field from the stellar corona. On the Sun, they mostly originate from active surface regions, such as groups of sun spots. Near solar maxima, the Sun produces about three events per day, falling to about one in five days near solar minima (e.g. Chen, 2011; Karpen et al., 2012; Webb & Howard, 2012).

Simulations of the effects of CMEs on the magnetospheres and ionospheres of hot Jupiters show that they may be a significant component of atmospheric loss (Khodachenko et al., 2007a; Cohen et al., 2011b; Bisikalo & Cherenkov, 2016; Kay et al., 2016; Cherenkov et al., 2017). Their impact on habitability will depend on shielding by any planetary magnetosphere (§11.7.3).

### 8.10.7 Energetic neutral atoms

In the solar system, *energetic neutral atoms* (ENAs) arise when energetic ions in the solar wind (e.g. H<sup>+</sup>, He<sup>2+</sup>), spiraling in the heliospheric or planetary magnetospheric fields, undergo charge exchange collisions with the background neutral gas (interstellar medium, or planetary exosphere). They become neutral, resulting in an energetic neutral atom and a 'cold' ion (proton–hydrogen charge exchange is the simplest example: H<sup>+</sup> + H → H + H<sup>+</sup>). Preserving the vector momentum of the original pre-interaction plasma ion, the ENA continues thereafter on a high-velocity rectilinear trajectory. The energies of the resulting neutral atoms ( $\sim 10$  eV–1 MeV) can be identified with the typical velocity dispersions of protons in the stellar wind.

**ENA mapping** The technique of *ENA mapping* of this hot gas (e.g. in Ly- $\alpha$ ) yields images of the planetary magnetosphere or heliosphere. Observed in space in the 1960–80s (e.g. Gruntman, 1997), dedicated ENA imaging cameras have since been flown, starting with Astrid–1 (SWE) to study Earth's magnetosphere in 1995. Magnetospheric images have since been obtained of Venus, Mars, Jupiter, and Saturn, including from Cassini and TWINS, as well as of the heliospheric boundary from IBEX and Cassini (see references in, e.g. Lammer et al., 2011b). ENAs have also been used to probe mass loss and stellar wind properties of solar-type stars by observing the interaction regions carved out by the collisions between stellar winds and the interstellar medium (e.g. Wood et al., 2002; Lammer et al., 2011b).

**Exoplanets** Energetic neutral atoms were put forward to explain high-velocity hydrogen around HD 209458 b, and to estimate its magnetospheric properties (Holmström et al., 2008; Ben-Jaffel & Sona Hosseini, 2010; Ekenbäck et al., 2010; Tremblin & Chiang, 2013; Khodachenko et al., 2017).

ENA mapping has since been considered for studying star–planet interactions more generally, and perhaps most favourably for M stars, emphasised in the context of the World Space Observatory-UV/Spektr-UV (Fossati et al., 2014b; Boyarchuk et al., 2016) and PLATO (e.g. Lammer et al., 2011a,b).



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# Brown dwarfs and free-floating planets

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**B**ROWN DWARFS ARE SUBSTELLAR OBJECTS, of comparatively low temperature and luminosity, too low in mass to sustain stable hydrogen fusion, but in which lower threshold nuclear reactions can still occur. Spanning the mass range  $\sim 13 - 80M_J$ , they occupy the domain between planets and stars. Originally termed as black dwarfs, the label ‘brown dwarf’ was introduced by Tarter (1976), and has been used thereafter.

Predicted in the early 1960s, and first discovered in 1995, several thousand brown dwarfs are now known, including a number within only 10 pc of the Sun.

Their phenomenology and properties overlap with higher-mass stars and lower-mass planets in many respects: as a product of the low-mass tail of star formation, many are now known to be accompanied by disks and low-mass (planet-like) companions. Their atmospheric properties, and associated models, overlap with those of the highly irradiated hot Jupiters, and their surface features are being mapped with similar techniques. They also appear as the upper end of the planetary mass distribution around normal stars, with similar formation processes.

## 9.1 Introduction

This section summarises their detection, identification, spectral characteristics, and other properties, and places them in the context of exoplanet studies. The connection is particularly important in understanding the nature of massive orbiting planets with  $M \gtrsim 13M_J$ , and of the ‘free-floating planets’ found in young open clusters and star-forming regions. The coolest known, Y dwarfs with temperatures of 400–450 K or lower, and masses of  $5 - 20M_J$ , bridge the gap between hotter brown dwarfs and gas giant planets. If orbiting a star, a Y dwarf would presumably be considered to be a gas giant planet.

To provide some context, the current picture is that the majority of brown dwarfs form from collapsing molecular cloud cores, in broadly the same way as stars. An additional environmental phenomenon, *turbulent fragmentation*, has been invoked to reflect the

large number of brown dwarfs (and sub-brown dwarfs) observed at the lower end of the mass spectrum.

In this process, brown dwarfs form and occur singly or as members of multiple systems (as for stars), and with their own analogues of circumstellar disks (accompanied by accretion, and also jets and outflows) as well as planetary-type companions.

This formation scenario appears to explain the low-mass objects found in young clusters and associations frequently referred to as ‘free-floating planets’. There may still exist ‘genuine’ free-floating planets, viz. created as a by-product of the planet formation process, and liberated from the host planetary system perhaps by a number of different processes (including planet–planet interactions, or stellar fly-bys), although no compelling examples have yet been identified.

Objects of brown dwarf mass are also known to exist in planetary systems, where they were created by the different processes considered as the paradigm for planet formation, but with masses placing them above the  $M \lesssim 13M_J$  planetary regime (e.g. Chabrier et al., 2014).

### 9.1.1 The role of fusion

Some thirty years before their discovery, theories had identified a stellar/substellar boundary at  $\sim 75-80M_J$ , depending on chemical composition (Kumar, 1963; Hayashi & Nakano, 1963). In the normal process of star formation, gravitational collapse releases energy which leads to increasing temperature and density, and to cores which become partially degenerate. Collapse halts when the sum of the normal gas pressure, and the free electron degeneracy pressure arising from the Pauli exclusion principle which acts as an energy sink, balances the gravitational potential.

**Upper mass limits** At solar metallicity, objects above  $\sim 78M_J$  reach the  $3 \times 10^6$  K core temperatures necessary to initiate hydrogen fusion, and become stars. Below  $\sim 74M_J$ , core temperatures never rise to the levels necessary for sustained hydrogen fusion, and these ‘failed stars’ are termed *brown dwarfs*. Transition objects in the range  $\sim 74-78M_J$  sustain core fusion for the first

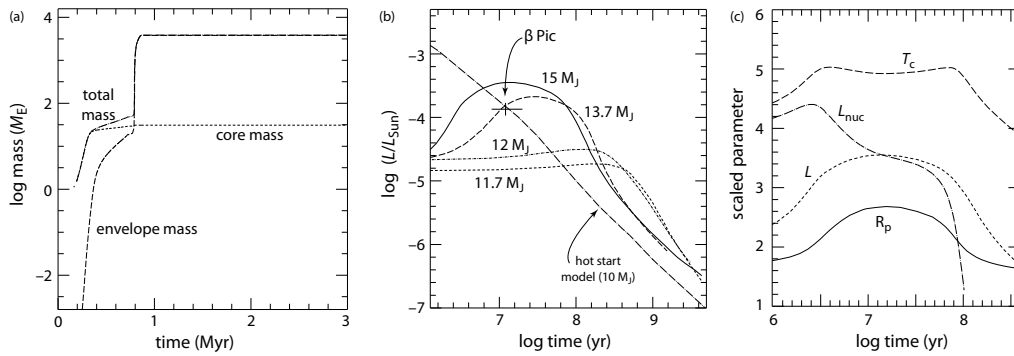


Figure 9.1: Deuterium burning simulations from the models of Bodenheimer et al. (2013), for their Run 2C ( $M_{\star} = 2M_{\odot}$ ,  $a = 9.5$  au,  $\sigma = 60$  kg m $^{-2}$ , etc.): (a) planet mass as a function of time during the formation phase, for a final planet mass of  $12M_{\text{J}}$ , showing the core mass (short-dash curve), the envelope mass (long-dash curve), and the total mass (dash-dot curve); (b) luminosity as a function of time during the post-formation deuterium-burning phase for four different planet masses. The long-dash dot curve shows a hot-start model for  $10M_{\text{J}}$  (Baraffe et al., 2003). The cross gives the position and error bars for the companion to  $\beta$  Pic (Bonnetfoy et al., 2013); (c) detail of the deuterium-burning phase for a  $15M_{\text{J}}$  planet showing, as a function of time, central temperature at the core/envelope interface,  $T_{\text{c}}$  (units of  $10^5$  K, long-dashed curve); nuclear luminosity (units of  $\log(L_{\text{nuc}}/L_{\odot}) + 7$ , dash-dot curve); radiated luminosity,  $L$  (same units, short-dashed curve); and the outer radius,  $R_{\text{p}}$  (units of  $5 \times 10^7$  m, solid curve). From Bodenheimer et al. (2013, Figures 6, 8, 10), by permission of IOP Publishing/AAS.

$10^9 - 10^{10}$  yr of their lifetime, before increasing degeneracy and falling temperatures transform them to brown dwarfs (D’Antona & Mazzitelli, 1985).

Decreasing metallicity leads to an increase in the mass of the stellar/substellar boundary, and to higher luminosities and effective temperatures at the H-burning limit. As given by Burrows et al. (2001), the boundary for solar composition is  $M \sim 0.07 - 0.074M_{\odot} \equiv 73 - 78M_{\text{J}}$ ,  $T_{\text{eff}} \sim 1700 - 1750$  K, and  $L \sim 6 \times 10^{-5}L_{\odot}$ ; while at zero metallicity  $M \sim 0.092M_{\odot} \equiv 96M_{\text{J}}$ ,  $T_{\text{eff}} \sim 3600$  K, and  $L \sim 1.3 \times 10^{-3}L_{\odot}$ . Uncertainties in silicate grain physics result in further ambiguities, with a boundary as low as  $T_{\text{eff}} \sim 1600$  K seemingly possible (Chabrier & Baraffe, 2000; Chabrier et al., 2000).

Below the H burning limit, lower threshold nuclear reactions may still occur: for solar metallicity, Li fusion above  $63-65M_{\text{J}}$  via the reaction  ${}^7\text{Li}(p,\alpha){}^4\text{He}$ , and deuterium (D or  ${}^2\text{H}$ ) fusion above  $\sim 13M_{\text{J}}$  via  ${}^2\text{H}(p,\gamma){}^3\text{He}$ .

**Lower mass limits** Below the deuterium-burning limit, which is again sensitive to chemical composition (including He and initial deuterium abundance), and which also depends on structural uniformity, nuclear processes, and the role of dust (Tinney, 1999; Spiegel et al., 2011), objects cannot sustain any species of nuclear burning in their interiors (Grossman & Graboske, 1973; Burrows et al., 1993; Saumon et al., 1996; Burrows et al., 1997, 2001).

A further consideration in defining the lower mass limit of brown dwarfs is the deuterium fraction which must fuse in order for an object to qualify as having ‘burned deuterium’. Although for most proto-brown dwarf conditions, 50% of the initial deuterium will burn if  $M \sim 13.0 \pm 0.8M_{\text{J}}$ , the deuterium-burning mass ranges

from  $\sim 11.0M_{\text{J}}$  for three times solar metallicity and 10% of initial deuterium burned, to  $\sim 16.3M_{\text{J}}$  for zero metallicity and 90% burned (Spiegel et al., 2011).

In principle, deuterium burning is also coupled to models of planet formation, with some sensitivity to whether accretion is described by the ‘hot start’ or ‘cold start’ assumptions, i.e. according to the contribution of the gravitational potential energy of the accreting material (§10.5.1). Simulations by Mollière & Mordasini (2012) find that the mass of the solid core has an influence on the minimum mass of deuterium burning in both scenarios, while the general position of the mass limit,  $13M_{\text{J}}$ , is not affected by more than  $\pm 0.8M_{\text{J}}$ . As a result of deuterium burning, the luminosity of hot and cold start objects becomes comparable after  $\sim 200$  Myr.

Detailed numerical simulations by Bodenheimer et al. (2013) yield comparable figures for the mass,  $M_{50}$ , above which more than 50% of the initial deuterium is burned. Their values fall in the range  $M_{50} = 11.6 - 13.6M_{\text{J}}$ , depending only slightly on parameters such as stellar mass, core mass, formation location, solid surface density in the protoplanetary disk, disk viscosity, and dust opacity. For masses above  $M_{50}$ , during the deuterium-burning phase, objects expand and increase in luminosity by one to three orders of magnitude, characterised by their evolutionary tracks in the luminosity versus time diagram (Figure 9.1).

Although not a directly observable quantity, the typical deuterium-fusion threshold of  $\sim 13M_{\text{J}}$  therefore sets a lower mass limit for objects classified as brown dwarfs. Below that mass, the terms planet, or sub-brown dwarf, will be used depending on their formation mechanism (box, page 431).

## 9.2 Discoveries and observations

### 9.2.1 The first brown dwarfs

The detection and characterisation of brown dwarfs in the solar neighbourhood, and in nearby young clusters and star-forming regions, has roughly paralleled that for exoplanets since their discovery. Even two decades after their predicted existence, finding brown dwarfs remained challenging because of their low luminosities and temperatures; even at their brightest in the near infrared they are still more than 8–10 mag fainter than solar-type stars. Searches in the 1980s and early 1990s failed to detect them, or at least were unable to confirm their substellar nature (e.g. Zuckerman & Becklin, 1987a; Stevenson, 1991; Basri, 2000b).

Even today, characterising them by mass, temperature and atmospheric composition has similarly remained a challenge (e.g. Tinney, 1999; Basri, 2000a; Reid & Metchev, 2008; Luhman, 2010).

Early candidates included companions to Van Biesbroeck 8 (McCarthy et al., 1985), unconfirmed by speckle interferometry (Perrier & Mariotti, 1987); to G29–38 (Zuckerman & Becklin, 1987b) much debated but finally shown to be a circumstellar disk (Greenstein, 1988; Graham et al., 1990; Kuchner et al., 1998); to HD 114762 (Latham et al., 1989) confirmed as a radial velocity companion but with uncertain mass; and to the white dwarf GD 165 (Becklin & Zuckerman, 1988).

Confirmation of demonstrably substellar mass came with the near-simultaneous discovery of two objects: the first isolated brown dwarf, the M8-type Teide 1 in the Pleiades (Rebolo et al., 1995), and the first brown dwarf companion to a normal star, the T6-type GJ 229 B at a distance of only 6 pc (Nakajima et al., 1995). With a 10 mag difference compared to its primary host star, GJ 229 B has an effective temperature of 1200 K, significantly below that of any H burning star, and a spectrum displaying strong CH<sub>4</sub> absorption, reminiscent of the solar system gas giants (Oppenheimer et al., 1995; Marley et al., 1996).

### 9.2.2 Brown dwarf surveys

Large area digital detectors sensitive in the near infrared (1–2  $\mu\text{m}$ ) changed the panorama of brown dwarf discoveries. Although these have not been focused exclusively on discovering brown dwarfs, this has frequently been an important part of their scientific goals (see reviews by Kirkpatrick, 2005; Burningham, 2014).

Following the Two Micron Sky Survey (TMSS, Neugebauer & Leighton, 1969), which scanned 70% of the sky and detected 5700 infrared sources, the late 1990s and early 2000s saw the advent of significantly deeper, wide-field far red/infrared sky surveys, notably DENIS, 2MASS, and SDSS. Among their scientific goals was the discovery of isolated brown dwarfs which, by

**Nomenclature:** This work will use a simplified nomenclature for distinguishing planets from brown dwarfs, based on their mass and their formation mechanism. Objects orbiting a star, and formed from a circumstellar gas disk, whether by core accretion (Lissauer, 1993) or by gravitational instabilities (Boss, 2002), are termed *planets* below the  $\sim 13M_J$  deuterium-fusion mass limit, and *brown dwarfs* (or brown dwarf planets) above it. Objects formed in the same way as stars, via rapid core collapse from molecular gas clouds (e.g. Bodenheimer et al., 1980b; Padoan & Nordlund, 2004), will again be termed *brown dwarfs* above this mass limit, but as *sub-brown dwarfs* below (Boss, 2001).

For the class of object referred to by their discoverers as ‘free-floating planets’, current evidence suggests that these have probably formed as the low-mass tail of the star formation process, and there is no evidence to suggest (neither is it claimed) that they have been ejected from planetary systems. For them, the term ‘sub-brown dwarf’ will be used. Planets gravitationally detached from their original host star presumably exist as a result of scattering processes, although no such cases are known, and the term *free-floating planet* or *ejected planet* will be used.

This nomenclature essentially follows that proposed by Boss et al. (2003), although it presupposes just two basic routes to the formation of planetary mass objects. Other issues are of relevance in classifying objects in the solar system, such as the type of orbit occupied (thus the Moon would have been considered a planet if orbiting the Sun directly, while Mercury would have been considered a satellite if orbiting Jupiter), the shape of the body (whether it is gravitationally relaxed), and whether it has cleared its region of planetesimals. A detailed discussion can be found in Basri & Brown (2006).

virtue of their intrinsic faintness and unknown properties, were at the time leading candidates to solve the problem of the Universe’s missing mass. Early results on space densities, however, swiftly ruled out brown dwarfs as the solution to the dark matter problem (e.g. Tinney, 1993; Kirkpatrick et al., 1994; Chabrier et al., 1996).

Because of the low luminosities of the coolest brown dwarfs, the census of even the nearest solar neighbourhood, within 10–20 pc, remains problematic. Deeper surveys with brown dwarf searches high in their priorities, have therefore continued to be developed.

Most survey discoveries are based on photometric selection exploiting the steep red slope of the 0.8–1.3  $\mu\text{m}$  spectral energy distribution.<sup>1</sup> Proper motion selection is an important alternative or complement, both for identifying photometric outliers, and for probing to the full depth of the survey where photometric contamination becomes more problematic.

There is a large and growing literature on brown dwarf searches, surveys, discoveries, properties, and

<sup>1</sup>The photometric systems and filters of relevance here are approximately *I* (0.79  $\mu\text{m}$ ), *J* (1.25  $\mu\text{m}$ ), *H* (1.60–1.65  $\mu\text{m}$ ), and *K/K<sub>s</sub>* (2.15–2.20  $\mu\text{m}$ ). A more comprehensive compilation is given at [en.wikipedia.org/wiki/Photometric\\_system](http://en.wikipedia.org/wiki/Photometric_system).

follow-up observations, and the following is intended to present only some of the development highlights.

**DENIS** The Deep near-infrared Southern Sky Survey (DENIS, Epchtein et al., 1997) surveyed the southern sky between 1995–2001 in the  $I$ ,  $J$ , and  $K_s$  bands using the ESO 1-m telescope at La Silla, generating a catalogue of 355 million point sources in its 2005 third release. Various brown dwarf candidates have been reported (e.g. Delfosse et al., 1999b; Delfosse & Forveille, 2001; Kendall et al., 2004; Martín et al., 2004; Phan-Bao et al., 2008a).

**2MASS** The Two Micron All Sky Survey (2MASS, Skrutskie et al., 2006) surveyed the entire sky between 1997–2001 from Mt Hopkins and Cerro Tololo in the  $J$ ,  $H$ , and  $K_s$  bands, generating the 2003 final-release catalogue of 300 million point sources with limiting magnitudes fainter than 15.8, 15.1, and 14.3 mag respectively. Brown dwarf discoveries with 2MASS have been extensively reported (e.g. Kirkpatrick et al., 1999; Burgasser et al., 2003b; Aberasturi et al., 2011).

**SDSS** The Sloan Digital Sky Survey (SDSS) is a multi-filter imaging and spectroscopic redshift survey using a 2.5-m wide-angle optical telescope at Apache Point Observatory, New Mexico (e.g. York et al., 2000; Geballe et al., 2002; Kirkpatrick, 2005). Data collection began in 2000, and the final imaging data release covers more than 35% of the sky, with photometry of ~500 million objects and spectra for more than 3 million.

The latest data releases include DR8, January 2011, including all photometric observations; DR9, July 2012, including first results from the Baryon Oscillation Spectroscopic Survey (BOSS) spectrograph; and DR10, July 2013, including first results from the APO Galactic Evolution Experiment (APOGEE) spectrograph. APOGEE included a survey of the CoRoT (APOCoRoT) and Kepler (APOKASC, Pinsonneault et al., 2014) fields.

Project phases are: SDSS I (2000–2005) devoted to imaging and spectroscopy; SDSS II (2005–2008) including the Sloan Legacy Survey, the SEGUE Milky Way survey, and the Sloan Supernova survey; SDSS III (2008–2014) including the APO Galactic Evolution Experiment (APOGEE), the Baryon Oscillation Spectroscopic Survey (BOSS), the Multi-object APO Radial Velocity Exoplanet Large-area Survey (MARVELS), and SEGUE-2; SDSS IV (2014–2020) with extended BOSS (eBOSS), APOGEE-2, and the nearby galaxy mapping MaNGA.

Several hundred L and T dwarfs have been discovered, including nearby objects confirmed by high proper motions derived from comparison with WISE and 2MASS (Scholz et al., 2011; Aberasturi et al., 2011).

**UKIDSS** The UK Infrared Digital Sky Survey (UKIDSS, Lawrence et al., 2007) has been operational at the 3.8-m UKIRT-WFCAM since 2005, and aims to cover 7500 sq. deg. of the northern sky. The large-scale near-infrared survey follows 2MASS (and is some 3 mag more

**Survey source designators:** Details of the naming conventions of all celestial objects, as ratified by the IAU Commission 5 Working Group on Designations, can be found at [cdsweb.u-strasbg.fr/cgi-bin/Dic](http://cdsweb.u-strasbg.fr/cgi-bin/Dic).

The 2MASS designator is described in the 2MASS Explanatory Supplement (Cutri et al., 2008), and is of the form 2MASxy Jhhmmss.ss±ddmmss.s, where  $xy$  corresponds to a specific catalogue and data release. For most sources of interest here, the pre-descriptor '2MASS' describes objects in the All-Sky Point Source Catalogue (others include 2MASSI, 2MASSs, 2MASSW, etc.). The remaining component gives the coordinate as sexagesimal right ascension and declination, with the decimal period optional.

Coordinates are truncated (and not rounded), and the 'J' indicates that the coordinate system is J2000 (as opposed to B1950). Strictly, modern coordinates are related to the ICRS, rather than to an equator/equinox, but since ICRS was constructed to be equivalent to J2000 (box, page 86), the 'J' may be understood as shorthand for ICRS.

Similarly, the designator for UKIDSS sources is of the form Uxxx Jhhmmss.ss±ddmmss.s, where Uxxx corresponds to ULAS, UDXS, UUDS, UGPS, or UGCS according to the survey, and where the U stands for UKIDSS.

The same considerations apply to the various catalogues and releases for CFBDS, DENIS, SDSS (where catalogue designators such as SDSSCG, SDSSp, etc., also exist), and WISE (with WISEA, WISEF, etc.).

Designator truncation is found widely in the literature. Thus 2MASSW J1207334–393254 can be found abbreviated to 2M J1207–3932, or even (as here) 2M J1207. The full coordinate designation should be evident, at least by context, to avoid confusion, e.g., if relying on literature searches using NED (NASA/IPAC Extragalactic Database).

sensitive) and preceded the ESO–VISTA telescope in the southern hemisphere. Of its four areas of scientific investigation, one targets the discovery and characterisation of the coolest and nearest brown dwarfs.

It comprises five surveys: three are optimised for extragalactic observations (the Large Area Survey, LAS; the Deep Extragalactic Survey, DXS; and the Ultra Deep Survey, UDS). Two are optimised for Galactic targets: the Galactic Plane Survey (GPS), covering 1800 sq. deg. in  $JHK$  to  $K = 19.0$ , and the Galactic Clusters Survey (GCS), covering 1400 sq. deg. in  $JHK$  to  $K = 18.7$ , and distributed over ten open clusters.

More than 300 L and T dwarfs have been discovered (Kendall et al., 2007a,b; Lodieu et al., 2007; Warren et al., 2007; Lodieu et al., 2009; Goldman et al., 2010; Burningham et al., 2013; Marocco et al., 2015), the nearest being a T dwarf companion to an L dwarf primary at 8 pc (Scholz, 2010).

**CFBDS and CFBDSIR** The Canada–France Brown Dwarf Survey (CFBDS, Delorme et al., 2008a,b), uses the optical wide-field CFHT–MegaCam to find ultracool dwarfs. More than 100 have been discovered.

A near-infrared extension, the Canada–France Brown Dwarf Survey Infrared (CFBDSIR), was undertaken with the expectation of discovering 10–15

dwarfs later than T8. Three candidates were initially reported by Delorme et al. (2010), with a Y candidate of  $T_{\text{eff}} \sim 370$  K inferred by Liu et al. (2011b).

**SIMP** SIMP (Sondage Infrarouge de Mouvement Propre) was a proper motion survey made with the CTIO–CPAPIR near-infrared camera (Artigau et al., 2006). Proper motions were constructed in combination with positions from 2MASS. Several discoveries have been reported (e.g. Artigau et al., 2009; Gagné et al., 2014).

**WISE** The Wide-field Infrared Survey Explorer (WISE, Wright et al., 2010) was a NASA MIDEX space mission, with a 0.4-m aperture, mapping the sky in four infrared bands (3.4, 4.6, 12, and 22  $\mu\text{m}$ , referred to as bands W1–W4 respectively). W1 and W2 were designed to probe the deep, 3.3  $\mu\text{m}$  CH<sub>4</sub> absorption band in brown dwarfs, and the region relatively free of opacity at  $\sim 4.6$   $\mu\text{m}$ .

WISE was launched in December 2009 into a Sun-synchronous polar orbit. The all-sky survey started in January 2010. The first full sky pass was completed on 2010 July 17, its second pass on 2011 January 9, during which bands W3 and W4 became unusable through cryogen exhaustion. A four-month mission extension (NEOWISE) was devoted to search for near-Earth objects. Data acquisition was halted on 2011 January 31, and re-activated in 2013 to search for near-Earth objects. By October 2010, it had discovered 33 500 new asteroids and comets, and observed 154 000 solar system objects.

Amongst several hundred brown dwarf discoveries are various ultracool Y dwarfs (Cushing et al., 2011; Mainzer et al., 2011; Rodriguez et al., 2011; Kirkpatrick et al., 2012), and its first 100 brown dwarfs (Kirkpatrick et al., 2011) which included 1 M, 8 L, 89 T, and 6 Y dwarfs. Some 10 are within 10 pc, and thus amongst the Sun's nearest neighbours, including WISE J1541–2250, at 2.8 pc, WISE J1049–5319 (Luhman 16AB), a binary brown dwarf at 2.0 pc (Luhman, 2013; Boffin et al., 2014), and WISE J0855–0714, at 2.3 pc, and with  $T_{\text{eff}} \sim 235 - 260$  K, the coolest known brown dwarf (Luhman, 2014b; Luhman & Esplin, 2014, 2016; Esplin et al., 2016). T dwarf and T/Y transition binaries have also been discovered from Keck laser guide star follow-up (Gelino et al., 2011; Liu et al., 2012).

**VISTA** The Visible and Infrared Survey Telescope for Astronomy (VISTA, Emerson & Sutherland, 2010; Cross et al., 2012; Sutherland et al., 2015) is a 4-m, 1.6° field infrared telescope at ESO Paranal. Equipped with the instrument VIRCAM, it operates between 0.85–2.3  $\mu\text{m}$  with broad-band filters at *Z*, *Y*, *J*, *H*, *K<sub>s</sub>*. Surveys began in early 2010. A second-generation instrument, 4MOST, a 2400-object fiber-fed multi-object spectrograph, is under development for installation around 2020.

There are six ESO Public Surveys being conducted, together expected to have a significant impact on brown dwarf discoveries in the coming years. These include

VHS (VISTA Hemisphere Survey) and VVV (VISTA Variables in the Via Láctea).

VHS (McMahon et al., 2013) will probe 5 times the volume of the UKIDSS LAS. A magnitude-limited sample of T dwarfs in the southern sky is being constructed with photometry from VHS in combination with WISE data, with the first results reported by Lodieu et al. (2012).

VVV is mapping the Galaxy bulge and southern Galactic plane to search for nearby brown dwarfs (Saito et al., 2012b; Beamín et al., 2013). The first, VVV BD001 (L5), was reported by Beamín et al. (2013).

**Pan-STARRS** The Panoramic Survey Telescope & Rapid Response System (Pan-STARRS, Kaiser, 2007) aims to detect potentially impacting near-Earth objects, surveying the sky visible from Hawaii to 24 mag, with the telescope funded by the US Air Force. Originally conceived as an array of four 1.8-m 3° telescopes, the first (PS1) began its survey in May 2010. PS2 commissioning began in mid-2014. Funding issues project no clear timeline for the remaining elements.

Proper motions allow the identification of brown dwarfs that would otherwise overlap with contaminant populations in near-infrared colours. It has proven useful for selecting L and T dwarfs as wide binary companions to stars (Deacon et al., 2012a,b, 2014). Parallaxes for nearby objects also opens the possibility of selecting nearby brown dwarfs purely on the basis of absolute photometry. A complete census of all stars within 25–100 pc has been suggested (Best et al., 2014). Discoveries include the late L dwarf PSO J318–22 which, at 6.5  $M_{\text{J}}$ , is one of the lowest mass free-floating objects in the solar neighbourhood (Liu et al., 2013c).

### 9.2.3 Future surveys

The next decade will see two surveys which could allow the detection of millions of brown dwarfs.

**Euclid** The 20 000 sq. deg. imaging survey carried out as part of the Euclid mission, scheduled for launch in 2020 (\$5.9.5), is expected to reach  $JHK \sim 23$ , allowing the selection and photometric typing of objects down to  $J \sim 20$  (Burningham, 2014).

**LSST** The Large Synoptic Survey Telescope at Cerro Pachón (\$6.4.4), with an 8.4-m aperture and 3.5° field, expects to start full operations for a 10-year survey in January 2023. Aiming to image the sky once every three nights, it should reach  $z \sim 28$  mag in its deep stacks by the end of the first decade.

The faint red survey limit will allow exploitation of Euclid to its full *J* band depth, representing a factor of 4000–8000 increase in searchable volume, with detectable brown dwarf numbers strongly dependent on the ability to photometrically classify L and T dwarfs (Burningham, 2014). Faint, nearby, fast-moving objects, including brown dwarfs, should also be detected.

### 9.2.4 Young clusters and star forming regions

Numerous searches for brown dwarfs in young clusters and star forming regions have also been conducted, e.g. in Cha I (Comerón et al., 2000), IC 348 (Luhman, 1999; Alves de Oliveira et al., 2013),  $\rho$  Oph (Alves de Oliveira et al., 2012; Mužić et al., 2012),  $\sigma$  Ori (Caballero, 2010; Caballero et al., 2012), Pleiades (Zapatero Osorio et al., 2014b), Sco–Cen (Janson et al., 2012d), Serpens (Spezzini et al., 2012), Taurus (Martín et al., 2001a; Briceño et al., 2002; Esplin & Luhman, 2017), and Upper Sco (Riaz et al., 2012b; Lodieu et al., 2013; Aller et al., 2013; Peña Ramírez et al., 2016; Lodieu et al., 2018).

The SONYC collaboration (Substellar Objects in Nearby Young Clusters) uses VLT–SINFONI, Subaru, and others, and has carried out discovery programmes in  $\rho$  Oph (Geers et al., 2011; Mužić et al., 2012), NGC 1333 (Scholz et al., 2009, 2012b,a, 2013), Cha I (Mužić et al., 2011, 2015), and Lupus 3 (Mužić et al., 2014, 2015).

Observations of young clusters and star forming regions also probe the lower end of the mass function. The detection of sub-brown dwarfs and objects of planetary mass is considered further in Section 9.9.

### 9.2.5 Other brown dwarf discoveries

In addition to the objects found from these specific surveys, there are many others which have been discovered either singly, or as binary companions to already known bright or nearby stars (e.g., from the HD, BD, GJ, LHS, NLTT, and HIP catalogues).

Others have been identified from microlensing surveys (OGLE, MACHO, MOA, and EROS), both as companions and as isolated objects (e.g., MACHO–179–A, Poindexter et al. 2005), more massive objects in exoplanet transit surveys (including CoRoT–3, CoRoT–15, CoRoT–33, KELT–1, Kepler–27, Kepler–53, Kepler–57, WASP–30), as planetary-type bodies found in debris disks (e.g., Fomalhaut b and  $\beta$  Pic b), as well as from ISO observations (e.g. Comerón et al., 1998), and others.

## 9.3 Follow-up observations

### 9.3.1 Observations from the ground

**Parallaxes** Parallaxes are important for quantifying physical properties, such as absolute fluxes, luminosities, and temperatures. The first programmes targeting brown dwarfs were carried out from the ground at red and near-infrared wavelengths, developing to embrace the 8–10 m telescopes, including Keck and Magellan (Dahn et al., 2002; Tinney et al., 2003a; Vrba et al., 2004; Marocco et al., 2010; Andrei et al., 2011; Dupuy & Liu, 2012; Faherty et al., 2012; Liu et al., 2013c; Manjavacas et al., 2013; Marocco et al., 2013; Smart et al., 2013; Tinney et al., 2014; Wang et al., 2014f; Zapatero Osorio et al., 2014a; Liu et al., 2016c; Weinberger et al., 2016).

Since near- to mid-infrared colours become rapidly redder toward the end of the T spectral sequence, parallaxes of late-T and Y dwarfs require the most sensitive near-infrared cameras, namely those on HST, and most recently employing the mid-infrared cameras on Spitzer and WISE (Dupuy & Kraus, 2013; Marsh et al., 2013; Beichman et al., 2014b).

**Spectroscopy and radial velocities** Radial velocity programmes have been undertaken to determine space velocities and associated kinematics. Measurements for 85 late M- and L-type very low-mass stars and brown dwarfs, mostly within 20 pc, and obtained with the Magellan Echellette spectrograph (Burgasser et al., 2015), confirm that most are members of the thin disk, with velocity dispersions indicating a mean age of  $5.2 \pm 0.2$  Gyr.

High-resolution spectroscopy of 25 field dwarfs (3 M, 16 L, 6 T) as part of the Keck–NIRSPEC Brown Dwarf Spectroscopic Survey (Prato et al., 2015), is providing high signal-to-noise spectra of relevance to atmospheric modeling, as well as constraints on orbital companions with periods up to a few years.

**High contrast imaging** Adaptive optics imaging has been used to search for binary companions of isolated young brown dwarfs. Example programmes include use of the Keck laser guide star system (Gelino et al., 2011; Liu et al., 2012) and VLT–NACO (Chauvin et al., 2012a).

### 9.3.2 Observations from space

Follow-up space observations of individual objects in the infrared have been made with ISO, operated between 1996–98 (e.g. Comerón et al., 1998); with Spitzer, operated between 2003–09, including the first low temperature Y dwarf companion to the white dwarf WD 0806–661 (Luhman et al., 2011, 2012), and the T8.5 dwarf Ross 458 C (Bunningham et al., 2011); and with the Japanese infrared satellite AKARI (ASTRO–F), operated between 2006–11 (Yamamura et al., 2010; Tsuji et al., 2011; Sorahana & Yamamura, 2012; Sorahana et al., 2013, 2014; Sorahana & Yamamura, 2014).

Time-resolved near-infrared spectroscopy with HST–WFC3 has been used to quantify rotational modulation as a probe of surface structure (through Doppler imaging), for example in the case of the two rotating L/T transition brown dwarfs 2M J2139+0220 and SIMP J0136 (Apai et al., 2013), and the two rotating L5 dwarfs 2M 1821+1414 and 2M 1507–1627 (Yang et al., 2015). Further details are given in Section 9.6.5.

ESA’s 3.5-m infrared/sub-mm Herschel satellite, operating in the SPIRE (250, 350 and 500  $\mu\text{m}$ ) and PACS (60–85/85–130 and 130–210  $\mu\text{m}$ ) imaging bands, included a programme to search for far infrared disk emission from cold dust around various young brown dwarfs. A number of detections, and associated constraints on disk masses, have been reported (e.g. Riaz & Gizis, 2012; Harvey et al., 2012b,a).

## 9.4 Current census

**Statistics** As of December 2015, the (latest available) online compilation of Johnston (2015) listed 3780 brown dwarfs, comprising 2850 confirmed and 930 candidate objects, including 644 M dwarfs, 1743 L dwarfs, 794 T dwarfs, 27 Y dwarfs, and 572 without spectral type.

Discovery rates, from the first candidates in 1984, are (approximately, with the listing being incomplete after 2011) 1984–89 (4), 1990–99 (116), 2000–09 (968), and 2010–15 (1265).

The majority of the 344 confirmed M dwarfs were discovered from 2MASS (124), DENIS (31), WISE (11), and UKIDSS (7). The majority of the 1563 confirmed L dwarfs were discovered from SDSS (629), 2MASS (423), UKIDSS (154), WISE (120), DENIS (107), and SIMP (3). The majority of the 706 confirmed T dwarfs were discovered from WISE (258), UKIDSS (188), SDSS (79), 2MASS (77), CFBDS (46), DENIS (2), and SIMP (2). Most of the 26 confirmed Y dwarfs were discovered from WISE (24).

**Field and binary occurrence** The majority of L and T dwarfs are isolated field objects, although some 15–20% occur as binaries, both as L dwarfs (Reid et al., 2008) and T dwarfs (Burgasser et al., 2003c).

**Lowest temperature** The coolest known brown dwarf is WISE J0855–0714 ( $d = 2.3$  pc), with  $T_{\text{eff}} \sim 235 - 260$  K (Luhman, 2014b; Luhman & Esplin, 2014).

**Proximity to the Sun** Of those objects with measured or estimated distances, 29 are within 6 pc (3M, 3L, 16T, 6Y, and one unknown type). A total of 550 are within 20 pc, and 1387 within 40 pc. Of those objects more distant than 40 pc, 757 are in young star clusters.

There are currently 56 known stellar systems within 5 pc of the Sun, comprising 60 stars (of which 50 are M dwarfs), 4 white dwarfs, and 13 L/T/Y dwarfs, the latter found both as isolated objects and as binary companions.<sup>2</sup> Of these, the L8/T1 binary WISE J1049–5319AB (Luhman 16A/B) is, at  $2.02 \pm 0.02$  pc, the third nearest system to the Sun (Luhman, 2013; Boffin et al., 2014), while the Y dwarf WISE J0855–0714, at  $2.31 \pm 0.08$  pc, is currently the fourth (Luhman & Esplin, 2014).

**Space densities** Marocco et al. (2015) estimated the local space density of field brown dwarfs, depending on binary fraction, as

$$\begin{aligned} 0.8 - 1.0 \times 10^{-3} \text{ pc}^{-3} & \text{ for L4–L6.5 dwarfs,} \\ 0.7 - 0.8 \times 10^{-3} \text{ pc}^{-3} & \text{ for L7–T0.5 dwarfs,} \\ 0.7 - 0.9 \times 10^{-3} \text{ pc}^{-3} & \text{ for T1–T4.5 dwarfs.} \end{aligned}$$

**Completeness** Skrzypek et al. (2016) constructed a homogeneous sample of 1361 L and T dwarfs (of which 998 are new) brighter than  $J = 17.5$  with accurate spectral

**MK classification:** The MK classification itself was built on the original Harvard sequence of spectral types, through a progressive revision of the list of defining standards (Morgan et al., 1943; Johnson & Morgan, 1953; Morgan & Keenan, 1973; Keenan, 1985). A convenient summary of its broader nomenclature is given by Garrison (2000).

As for stars, the progressive brown dwarf spectral types are broadly a decreasing function of temperature, but with classification in practice based on their spectral features. As described by Morgan & Keenan (1973) ‘*The MK system is a phenomenology of spectral lines, blends, and bands, based on a general progression of colour index and luminosity. It is defined by an array of standard stars, located on the two-dimensional spectral type versus luminosity class diagram. These standard reference points do not depend on values of any specific line intensities or ratios of intensities; they have come to be defined by the appearance of the totality of lines, blends, and bands in the ordinary photographic region. The definition of a reference point, then, is the appearance of the spectrum ‘as in’ the standard star.*’

types, from an area of 3070 sq. deg., using observations from SDSS, UKIDSS, and WISE. The sample is considered to be effectively complete to the  $J = 17.5$  magnitude limit, for all spectral types L0–T8.

**Populations** Most brown dwarfs are members of the thin disk population, with velocity dispersions indicating a mean age  $5.2 \pm 0.2$  Gyr (Burgasser et al., 2015). Some metal-poor objects are known with halo kinematics, including the first known L dwarf 2MASS 0532+8246 (Burgasser et al., 2003a), indicating that star formation occurred below the H-burning mass limit at early times.

## 9.5 Classification

Brown dwarfs are classified spectroscopically through an extension of the MK stellar spectral type sequence, viz. OBAFGKM(SRN), as M, L, T and Y (Figure 9.2). Collectively, late-M, L and T dwarfs are also known as *ultra-cool dwarfs* (Kirkpatrick, 2005).

Atmospheric temperatures range from 2000–3000 K down to 500–600 K, so that their thermal emission lies primarily beyond  $1 \mu\text{m}$ , e.g. peaking at  $1.5 \mu\text{m}$  for a  $T_{\text{eff}} = 2000$  K black body. Low and decreasing temperatures through the late M, L, and T sequence result in a wide variety of near-infrared spectral features as brown dwarfs age and cool, from relatively narrow lines of neutral atoms to broad molecular bands, all of which may have different dependencies on  $T_{\text{eff}}$ ,  $\log g$ , and  $[\text{Fe}/\text{H}]$ .

That some class M and L objects are stars and some are brown dwarfs arises because some of the youngest (low-mass) brown dwarfs can have the same  $T_{\text{eff}}$  as the higher mass stars, and therefore similar spectral characteristics. Equivalently, the atmospheric gas and cloud chemistry in brown dwarfs and gas giants is similar for corresponding values of  $T_{\text{eff}}$  (Faherty et al., 2016).

The low temperature conditions accelerate conden-

<sup>2</sup>A schematic of this local population is at [en.wikipedia.org/wiki/List\\_of\\_nearest\\_stars\\_and\\_brown\\_dwarfs](https://en.wikipedia.org/wiki/List_of_nearest_stars_and_brown_dwarfs)

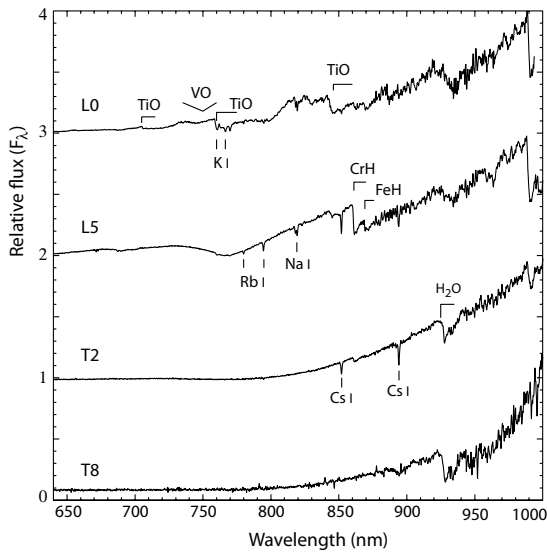


Figure 9.2: Optical spectra of L and T-type brown dwarfs.  $T_{\text{eff}}$  ranges from  $\sim 2100$  K at L0 to  $\sim 900$  K at T5. Prominent spectral features are labeled. From Reid & Metchev (2008, Figure 3).

sation out of the gas state and into the formation of grains, such that the effects of condensates, clouds, molecular abundances, and atomic opacities are all important in interpreting their spectral properties. In the case of orbiting rather than isolated brown dwarfs, supplementary irradiation by the central host star further affects their reflection spectra and albedos. Despite these complexities, evolutionary models broadly explain the systematic features of substellar mass objects over three orders in mass and age, and some factor 30 in temperature (e.g. Burrows et al., 2001).

**Spectral features** As brown dwarfs cool and evolve down the spectral sequence (through the M, L, T and Y spectral classes), their spectral energy distributions become increasingly complex as molecular species progressively dominate photospheric opacity.

These compounds include condensates: minerals and metals in the atmospheres of late-M and L dwarfs (Lunine et al., 1989; Tsuji et al., 1996), sulphide and alkali salts in late-T and Y dwarfs (Burgasser et al., 2010b; Morley et al., 2012). Grain scattering and absorption cause a significant redistribution of flux, the veiling of molecular bands, changes in the gas chemistry, and the modification of cooling rates, with non-equilibrium mixing effects playing an increasingly important role (Fegley & Lodders, 1994; Griffith & Yelle, 1999; Saumon et al., 2006; Hubeny & Burrows, 2007). Variability, accentuated by rotation, occurs if the condensates are not uniformly distributed in the photosphere (Allard et al., 2001; Ackerman & Marley, 2001; Burrows & Sharp, 1999; Saumon & Marley, 2008; Radigan et al., 2012, see §9.6.5). Condensate clouds are now used in the spectral fits of both

brown dwarfs (e.g. Stephens et al., 2009), and directly-imaged giant exoplanets (e.g. Currie et al., 2011a; Barman et al., 2011a; Skemer et al., 2012; Marley et al., 2012).

Between 2000–3000 K, the defining characteristics of spectral class M are an optical spectrum dominated by the metal-oxide absorption bands of TiO and VO, with metal hydride (MgH, CaH) absorption in the optical and H<sub>2</sub>O bands in the near infrared becoming more prominent in the later spectral types.

Below 2000–2100 K, L dwarfs are characterised by strong metal hydride bands (FeH, CrH, MgH, CaH), prominent alkali metal lines (NaI, KI, CsI, RbI), and strong near-infrared absorption of H<sub>2</sub>O and CO (Kirkpatrick et al., 1999; Basri et al., 2000). Below 1700 K, CH<sub>4</sub> forms in the outer atmosphere.

As they cool below about 2300 K, liquid or crystalline particles composed of calcium aluminates, silicates and iron condense into atmospheric ‘dust’, which disappears at still cooler temperatures (around 1300 K). Models to explain this dust dispersal include both an abrupt sinking of the entire cloud deck into the deep, unobservable atmosphere and breakup of the cloud into scattered patches (as seen on Jupiter and Saturn).

Below 1200–1300 K, T dwarfs are characterised by prominent CH<sub>4</sub> absorption (Burgasser et al., 2002a; Zahnle & Marley, 2014). Atmospheres are sufficiently cool for H<sub>2</sub>O and CH<sub>4</sub> to form in abundance, resulting in distinct, planet-like spectra (Oppenheimer et al., 1995; Geballe et al., 1996). Some of the coolest known, of spectral class T8–T9, have  $T_{\text{eff}} \sim 650 - 700$  K (Leggett et al., 2009; Burgasser et al., 2010b).

Below 500–600 K, NH<sub>3</sub> absorption is predicted to make a significant contribution to the near- and mid-infrared spectrum, along with scattering from water ice clouds (Kirkpatrick, 2005; Burrows et al., 2003b). An additional Y class, with prototypes and distinguishing spectral features, was proposed to encompass such objects (Burrows et al., 2003b; Burningham et al., 2008; Delorme et al., 2008a; Eisenhardt et al., 2010; Lucas et al., 2010; Kirkpatrick et al., 2012). Example theoretical predictions are shown in Figures 9.3 and 9.4.

Identification and classification of L and T dwarfs using photometry alone, without the need for spectroscopy, has been demonstrated by Skrzypczek et al. (2015).

**The first Y dwarfs** Although more than 200 T dwarfs had been discovered by 2010, there remained a large gap in temperature between the coolest known ( $T_{\text{eff}} \sim 500$  K) and the Jovian planets ( $T_{\text{eff}} \sim 150$  K). Spitzer–IRAC observations provided a candidate for the first low temperature Y dwarf, a companion to the white dwarf WD 0806–661. With  $T_{\text{eff}} \sim 300$  K and  $M \sim 7M_{\text{J}}$ , it could be a brown dwarf which formed like a binary star, or a giant planet born within a disk and dynamically scattered to a larger orbit (Luhman et al., 2011). Others have since been discovered by WISE (e.g. Gelino et al., 2011; Cushing et al.,



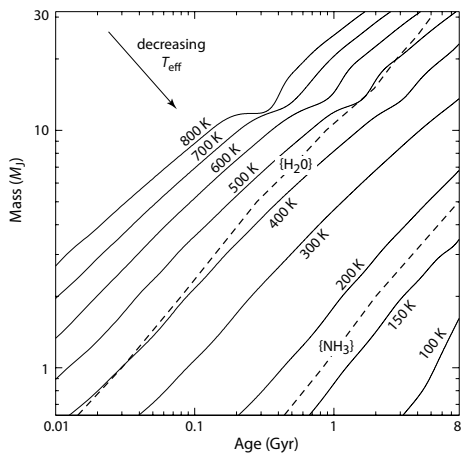


Figure 9.3: Brown dwarf mass versus age for  $T_{\text{eff}} < 800$  K. At constant mass, increasing age corresponds to a declining  $T_{\text{eff}}$ . The condensation curves for  $\text{H}_2\text{O}$  and  $\text{NH}_3$  (dashed lines) indicate ages at which condensation first occur in the outer atmosphere. The kink near  $13M_J$  is a consequence of deuterium burning. From Burrows et al. (2003b, Figure 2), by permission of IOP Publishing/AAS.

2011), including the very cool ( $T_{\text{eff}} \sim 250\text{--}400$  K,  $3\text{--}6M_J$ ) WISE J1828+2650 (Beichman et al., 2013), and the current low-temperature record holder WISE J0855–0714, at 2.3 pc, and with  $T_{\text{eff}} \sim 235\text{--}260$  K (Luhman, 2014b; Luhman & Esplin, 2014).

**Recognising brown dwarfs** Distinguishing high-mass brown dwarfs from low-mass stars primarily relies on accurate estimates of temperature and luminosity. Atmospheric  $\text{CH}_4$  can be accumulated by older brown dwarfs, as for the T dwarf prototype GJ 229 B (Nakajima et al., 1995), and its spectral presence rules out an object of stellar mass. The presence of lithium may also suggest that the object is substellar, although very young stars may contain residual unburned lithium, while more massive objects like the Sun can retain lithium in their cooler convective atmospheres. Conversely, the more massive brown dwarfs,  $\geq 65M_J$ , may be hot enough to deplete their lithium when young. A weakening at lower gravities is also predicted from model atmospheres (Kirkpatrick et al., 2008).

The lower temperature range of the L dwarfs, 700–2000 K overlaps with the upper range of the ‘hot Jupiters’, whose predicted temperatures are expected to reach 1200–1500 K. In consequence, there are expected to be similarities in their spectral appearance, as well as in their atmospheric temperature/density profiles.

The weak mass–radius dependence means that only density rather than radius can distinguish low-mass brown dwarfs from high-mass planets (Luhman, 2008).

**J-band brightening and flux reversal binaries** The L/T transition is characterised observationally by an in-

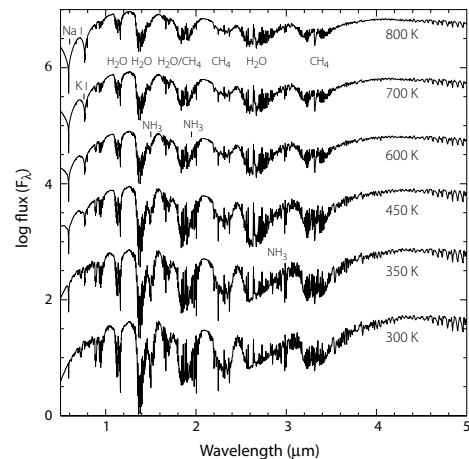


Figure 9.4: Expected spectroscopic characteristics of cool brown dwarfs in the range covered by JWST–NIRSpec, based on the model calculations by Burrows et al. (2003b). The main spectral features expected at the various temperatures are identified.  $\text{NH}_3$  appears below  $\sim 600$  K, and the alkali metal lines (Na I, K I), shortward of  $1\ \mu\text{m}$ , weaken below  $\sim 450$  K. From Reid & Metchev (2008, Figure 13).

crease in the J-band luminosity with decreasing temperature over the 1400–1100 K interval, somewhat unexpected behaviour referred to as the *J-band brightening* (Tinney et al., 2003a; Vrba et al., 2004; Artigau et al., 2009; Faherty et al., 2012).

Although the brightening coincides with the disappearance of silicate grains from the brown dwarf atmosphere (§9.5), its physical interpretation remains under some debate: it may be evidence of a rapid disruption of the condensate cloud layer (Burgasser et al., 2002b; Knapp et al., 2004) or a slow evolutionary process of heat release (Burgasser et al., 2002b; Knapp et al., 2004), while the degree of brightening may be modulated by variations in other parameters, such as rotation, viewing angle, or cloud thickness (Burrows et al., 2006a; Burgasser et al., 2010a).

Resolved brown dwarf binaries have been useful in clarifying the parameters relevant to condensate formation and evolution, as their common distance and genesis eliminates many of the uncertainties in their (relative) physical and spatial characteristics. Such systems are also amenable to direct mass measurement (e.g. Lane et al., 2001; Dupuy et al., 2009; Konopacky et al., 2010), allowing direct comparison to and tests of evolutionary models. Binaries with L dwarf and T dwarf components have been particularly valuable in probing the disappearance of mineral clouds at this spectral transition. A handful are found to be *flux-reversal* pairs, in which the later-type secondary is brighter in the 1.0–1.3  $\mu\text{m}$  region than its earlier-type (and overall more luminous) primary (Burgasser et al., 2006; Liu et al., 2006;Looper et al., 2008a; Burgasser et al., 2013). These bi-

naries confirm that the  $J$ -band brightening originally found for field L and T dwarfs is a general feature of brown dwarf evolution.

Dusty models containing no grain sedimentation can reproduce the behaviour of late-M to mid-L dwarfs, condensed (clear) models, where the grains are entirely removed from the atmospheres, accurately describe mid-to-late-T dwarfs. Models including grain settling and precipitation can reproduce a flattening of the  $J$ -band magnitude over the relevant temperature interval (Burrows et al., 2006a). If clearings in an otherwise cloudy atmosphere are (partially) responsible (Ackerman & Marley, 2001; Burgasser et al., 2002b) photometric variability may follow from the rotation and/or evolution of the cloud pattern.

**Underluminosity** Most directly imaged giant planets are redder, and up to 4–10 times fainter, than typical brown dwarfs of the same spectral type. This has been referred to as the *underluminosity problem* (e.g. Barman et al., 2011b; Skemer et al., 2012; Apai et al., 2013).

Examples include Ross 458C (Burgasser et al., 2010a; Burningham et al., 2011; Morley et al., 2012) and 2M J1207 b (Chauvin et al., 2005a; Mohanty et al., 2007; Patience et al., 2010; Barman et al., 2011b; Skemer et al., 2011; Zhou et al., 2016d). Similar underluminosity has been found for some field brown dwarfs, e.g. HD 203030B (Metchev & Hillenbrand, 2006), HN Peg B (Luhman et al., 2007b), 2MASS J18212815 and 2MASS J21481628 (Looper et al., 2008b), as well as a number of young brown dwarfs in clusters (Lucas et al., 2001; Allers et al., 2006).

Models proposed to explain these different near-infrared luminosities invoke differences in elemental abundances, surface gravity differences, evolutionary state, chemical equilibrium/non-equilibrium, or cloud structure. Possible differences in the structure of condensate clouds have received much attention (e.g. Ackerman & Marley, 2001; Burgasser et al., 2002b; Skemer et al., 2012; Barman et al., 2011a,b; Burrows et al., 2006a; Madhusudhan et al., 2011a; Marley et al., 2010), with spectroscopic modeling aiming to separate the impact of cloud structure from other parameters (e.g. Cruz et al., 2007; Folkes et al., 2007; Looper et al., 2008b; Burgasser et al., 2008; Radigan et al., 2008; Cushing et al., 2010).

## 9.6 Physical properties

### 9.6.1 Luminosity and age

Once their nuclear energy source is exhausted, brown dwarfs cool and dim, with density playing an important role (Chabrier et al., 2009). At the upper mass range,  $\sim 75 - 80M_J$ , the density of a brown dwarf is set by electron degeneracy pressure as in white dwarfs, while at the lower end,  $10 - 20M_J$ , it is set primarily by Coulomb pressure, as in planets. The result is that the radii of all brown

dwarfs are approximately  $1R_J$ , varying by only 10–15% over  $\sim 10 - 80M_J$  (Figure 6.100).

Solar-metallicity power-law relations which characterise the evolution of older substellar mass objects (Burrows & Liebert, 1993; Marley et al., 1996) are summarised by Burrows et al. (2001, eqn 1–5) as

$$\begin{aligned} L &= 4 \times 10^{-5} L_{\odot} \left( \frac{10^9 \text{ yr}}{\tau} \right)^{1.3} \left( \frac{M}{0.05 M_{\odot}} \right)^{2.64} (10^3 \kappa_R)^{0.35} \\ T_{\text{eff}} &= 1550 \text{ K} \left( \frac{10^9 \text{ yr}}{\tau} \right)^{0.32} \left( \frac{M}{0.05 M_{\odot}} \right)^{0.83} (10^3 \kappa_R)^{0.088} \\ M &= 35 M_J \left( \frac{g}{10^3} \right)^{0.64} \left( \frac{T_{\text{eff}}}{1000 \text{ K}} \right)^{0.23} \\ \tau &= 1.0 \text{ Gyr} \left( \frac{g}{10^3} \right)^{1.7} \left( \frac{1000 \text{ K}}{T_{\text{eff}}} \right)^{2.8} \\ R &= 6.7 \times 10^4 \text{ km} \left( \frac{g}{10^3} \right)^{-0.18} \left( \frac{T_{\text{eff}}}{1000 \text{ K}} \right)^{0.11}, \end{aligned} \quad (9.1)$$

where  $\tau$  is the age,  $g$  the surface gravity ( $\text{m s}^{-2}$ ), and  $\kappa_R$  is an average Rosseland mean opacity ( $\text{m}^2 \text{ kg}^{-1}$ ).

The weak dependence of radius on mass and temperature means that all brown dwarfs follow a similar trajectory in the  $(L, T_{\text{eff}})$  plane. Deriving the mass from its  $L$  or  $T_{\text{eff}}$  therefore requires an estimate of its age. For example, a brown dwarf with  $L \sim 10^{-4} L_{\odot}$  could be a  $70M_J$  object at  $\tau = 10^9$  yr, or a  $10M_J$  sub-brown dwarf at  $\tau = 10^7$  yr (e.g. Burrows et al., 2001, their figure 1).

The longer cooling time of the more massive objects suggests that most field brown dwarfs should lie at the upper end of the allowed mass range. Relatively small numbers show spectral features suggestive of low surface gravities (strong VO absorption, weaker alkali metal lines, and weaker hydride bands), implying lower masses and younger ages (Kirkpatrick et al., 2008; Cruz et al., 2009). Cruz et al. (2009) accordingly proposed an extension of the spectral classification for L0 to L5-type dwarfs to include three gravity classes.

### 9.6.2 Radius

The more detailed evolutionary models of Burrows et al. (2011), which account for different atmospheric metallicities ( $[\text{Fe}/\text{H}]$ ), with and without clouds, suggest a slightly larger spread in radius at a given mass and age, reaching 10–25%, with higher-metallicity, higher-cloud-thickness atmospheres resulting in larger radii. For example, for each 0.1 dex increase in  $[\text{Fe}/\text{H}]$ , radii increase by 1–2.5%, depending on age and mass. For smaller masses and older ages, radii decrease with increasing helium fraction ( $Y$ ), while for more massive brown dwarfs and a wide range of ages they increase with helium fraction.

They emphasise that transit and eclipse measurements of brown dwarf radii, rather than probing some

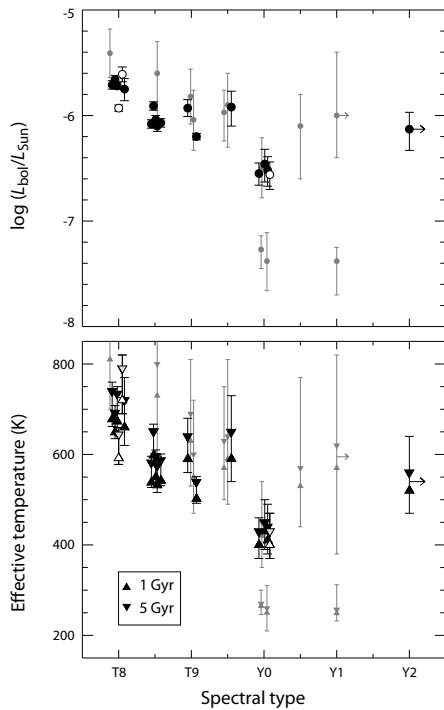


Figure 9.5: Bolometric luminosities,  $L_{\text{bol}}$  (top) and  $T_{\text{eff}}$  (bottom) for brown dwarfs of spectral type T8 and later. Objects with  $\sigma(L_{\text{bol}}) > 0.2$  dex (uncertain distances, or components of tight binaries) are shown as small grey symbols. Spectrally peculiar objects are shown as white symbols. Upward and downward pointing triangles correspond to the median  $L_{\text{bol}}$  and lower and upper age limits. Error bars show temperature ranges corresponding to  $\pm 1\sigma$  in  $L_{\text{bol}}$ . From Dupuy & Kraus (2013, Figure 4), reprinted with permission from AAS.

universal mass–radius relation, constrain numerous effects collectively, including the atmosphere and condensate cloud models as well as the equation of state.

### 9.6.3 Temperature

Properties of the cooler dwarfs, and especially the Y dwarfs, remain somewhat uncertain given the uncertainty in their temperatures, ages, and luminosities. Temperatures are only typically estimated from model atmospheres that use incomplete molecular line lists, and simple prescriptions for complex processes like non-equilibrium chemistry and condensate formation.

Dupuy & Kraus (2013) derived temperatures of 16 Y dwarfs by combining bolometric luminosities ( $L_{\text{bol}}$ ) derived from accurate parallaxes and multi-wavelength photometry, with evolutionary model-predicted radii ( $R_{\star}$ ) and applying the Stefan–Boltzmann Law,  $T_{\text{eff}} \equiv (4\pi\sigma R_{\star}^2/L_{\text{bol}})^{1/4}$  (Figure 9.5). Observations of transiting exoplanets generally confirm evolutionary model radius predictions over a wide range of masses (e.g. Deleuil et al., 2008; Hellier et al., 2009a; Anderson et al., 2011c).

### 9.6.4 Magnetic field

Relatively little is known about the magnetic fields of brown dwarfs or exoplanets. Unlike the slowly rotating Sun (box, page 650), the magnetic fields of Earth and Jupiter, along with those of rapidly rotating, low-mass stars, are generated by convection-driven dynamos. While the field strengths of planets and stars vary over three orders of magnitude, an extension of a scaling law derived from geodynamo models to rapidly rotating stars with strong density stratification has been shown to fit the observed field strengths of Earth, Jupiter, young contracting stars and rapidly rotating low-mass stars, despite substantial differences in their physical conditions (Christensen et al., 2009a).

Reiners & Christensen (2010) estimated the evolution of average magnetic fields in extrasolar planets and brown dwarfs under the assumption of fast rotation. They found that massive brown dwarfs ( $\sim 70M_{\text{J}}$ ) can have fields 0.1–0.5 T during the first few hundred Myr, which can subsequently grow by a factor two before they weaken after deuterium burning has ceased. Brown dwarfs with weak deuterium burning and extrasolar giant planets start with magnetic fields between  $\sim 10^{-2} - 10^{-1}$  T at an age of a few Myr, depending on mass. Their magnetic field weakens steadily until after 10 Gyr it has shrunk by about a factor of 10. X-ray luminosities can then be used to estimate ages of giant exoplanets with  $M_{\text{p}} \geq 0.3M_{\text{J}}$  and closer than 20 pc.

From their estimated age, and assuming Sun-like wind-properties and radio emission processes similar to those of Jupiter, their predicted radio flux can be estimated as a function of frequency. Most planets are then expected to emit radiation between a few MHz and 100 MHz, well above the ionospheric cut-off frequency. Further aspects of the radio emission expected from brown dwarfs and exoplanets are given in Section 8.10.5.

### 9.6.5 Variability, rotation, and condensate clouds

Many brown dwarfs are now known to show photometric variations in the infrared (e.g. Biller, 2017). They are attributed to rotational manifestation of surface inhomogeneities, in turn attributed to patchy clouds, and with the implied existence of extreme wind and weather patterns (e.g. Tinney & Tolley, 1999; Bailer-Jones & Mundt, 2001; Morales-Calderón et al., 2006; Heinze et al., 2015), analogous to those observed on Jupiter and, through secondary eclipse observations, of transiting exoplanets. Specifically, growth of heterogeneities in the cloud cover may account for the L- to T-type transition as their photospheres evolve from cloudy to clear conditions, a hypothesis at least qualitatively compatible with rotational variability (§9.5).

**Examples** Early searches for photometric variability concentrated mostly on L dwarfs in the *I* band, and established that

roughly half display variability on time scales ranging from tens of minutes to weeks, with amplitudes of a few tens of mmag (Terndrup et al., 1999; Tinney & Tolley, 1999; Bailer-Jones & Mundt, 2001; Martín et al., 2001c; Gelino et al., 2002).

Subsequent studies showed that variability extends down to the L/T transition (e.g. Enoch et al., 2003; Koen et al., 2004, 2005; Morales-Calderón et al., 2006; Clarke et al., 2008; Goldman et al., 2008; Artigau et al., 2009; Heinze et al., 2015).

Apai et al. (2013) reported time-resolved near-infrared spectroscopy of two rotating L/T transition brown dwarfs (2M J2139 and SIMP J0136) with HST. Both displayed *J*- and *H*-band brightness variations. Spectral changes could be reproduced with a linear combination of two different spectra, implying that the entire surface is covered by two distinct types of region. Modeling the colour changes and spectral variations together reveal patchy cloud covers consisting of a spatially heterogeneous mix of low-brightness, low-temperature thick clouds and brighter, thin, and warm clouds. Extended to the entire photosphere, the same thick cloud patches would imply near-infrared magnitudes and colours matching the range occupied by the directly imaged exoplanets that are cooler and less luminous than brown dwarfs with similar spectral types. These results support a model in which thick clouds are responsible for their near-infrared properties (§9.5).

This type of time-resolved photometry, with its insight into longitudinal and vertical cloud structures and evolution, has become an important probe of the physics of condensate clouds in extrasolar planets and brown dwarfs. Rotationally-driven brightness variations, attributed to ‘patchy clouds’ and evolving ‘weather’, have since been observed in other brown dwarfs, including WISE J1049–5319 (Luhman 16AB) observed with GROND (Biller et al., 2013a); 69 L0–T8 dwarfs with NTT-SofI (Wilson et al., 2014b); 62 L4–T9 dwarfs with the Du Pont 2.5-m and CFHT (Radigan et al., 2014); two L5 dwarfs observed with HST-WFC3, where the variability is attributed to the presence of spatially varying high-altitude haze layers above the condensate clouds (Yang et al., 2015); 44 L3–T8 dwarfs observed with Spitzer, confirming that such patches are ubiquitous on L and T dwarfs (Metchev et al., 2015); and 12 T dwarfs observed at Kitt Peak at 700–950 nm (Heinze et al., 2015).

**Two-dimensional surface mapping** Globally integrated measurements can reveal surface inhomogeneities but cannot unambiguously resolve surface features. In contrast, a 2d map of a brown dwarf surface, isolating large-scale bright and dark features indicative of patchy clouds, was reported by Crossfield et al. (2014) for Luhman 16AB (WISE J1049–5319; Luhman, 2013; Kniazev et al., 2013; Burgasser et al., 2013).

The system comprises two brown dwarfs at  $d \sim 2$  pc, a proximity making them the first substellar objects bright enough to be studied at high precision and high spectral resolution on short time scales. Both are near the dust-clearing temperature. Luhman 16B exhibits strong temporal variability of its thermal radiation consistent with a rapid rotation period of 4.9 h. Observations with VLT-CRIRES, and Doppler imaging reconstruction on a  $10 \times 20$  grid, produces a map that shows a large dark mid-latitude region, a brighter area on the opposite hemisphere located close to the pole, and other structures at equatorial latitudes (Figure 9.6).

**Doppler imaging:** The technique of *Doppler imaging* produces two-dimensional maps of rotating objects using high-resolution spectroscopy, exploiting the varying Doppler shifts across a rotating object. In astronomy, it was developed to map the inhomogeneous surfaces of rotating stars (e.g. Vogt et al., 1987; Rice et al., 1989).

Qualitatively, as darker regions cross the surface, the Doppler-broadened absorption lines exhibit deviations at the projected radial velocities of the darker areas. Features near the equator cause changes across the entire line profile and move across the full span of velocities; features at higher latitudes move more slowly, experience smaller Doppler shifts, and affect a narrower velocity range.

The technique offers the prospects of detailing global atmospheric dynamics and magnetic effects in brown dwarfs and exoplanets. Based on available photometric variability, rotation period, and projected rotational velocity for all known brown dwarfs, Crossfield (2014) demonstrated that several bright objects were already accessible to Doppler imaging, with the greatest sensitivity in the K band and, to a lesser extent, in H and L. With the advent of extremely large telescopes, Doppler imaging should become feasible for several dozen brown dwarfs and for the few brightest directly imaged exoplanets such as  $\beta$  Pic b.

A natural explanation for these features is the presence of the patchy global clouds inferred to exist from multi-wavelength variability. In this interpretation, the dark areas represent thicker clouds that obscure deeper, hotter parts of the atmosphere and present a higher-altitude (and thus colder) emissive surface, whereas bright regions correspond to holes in the upper cloud layers that provide a view of the hotter, deeper interior.

The high-latitude bright spot could be similar to the polar vortices on Jupiter and Saturn, and predicted to exist on highly irradiated gas giants in short-period orbits around other stars (Cho et al., 2003).

**Extension to planetary mass companions** The same type of analysis has been extended to the planetary mass companion 2M J1207 b observed with HST-WFC3 (Zhou et al., 2016d). It shows amplitude modulation in the F125W and F160W filters of  $\sim 1\%$ , with a consistent period of  $10.7 \pm 0.9$  h and similar phases in both bands. Attributed to rotation, it represents the first determination of a rotation period for a directly imaged exoplanet (as opposed to a planetary spin rate determination, cf. Section 2.5.4). These various planetary spin rate/rotation determinations are collected together in Figure 12.15.

Results for the 4-planet system HR 8799 observed with VLT-SPHERE are given by Apai et al. (2016).

### 9.6.6 X-ray and radio emission

Convection combined with rapid rotation leads to the development of tangled magnetic fields near their surface, reaching 0.01–0.1 T (Berger, 2006). Quiescent X-ray emission, first detected for Cha H $\alpha$ 1 (Neuhäuser & Cameron, 1998), as well as X-ray flares, first detected for

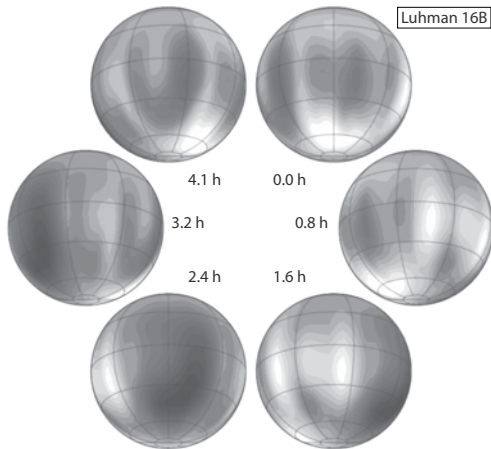


Figure 9.6: Surface mapping of the brown dwarf Luhman 16B (WISE J1049–5319). Doppler imaging reveals a bright near-polar region (upper-right schematics) and a darker mid-latitude area (lower-left), consistent with large-scale cloud inhomogeneities. The lightest and darkest regions correspond to brightness variations of  $\pm 10\%$ . The time index of each projection is indicated, while monitoring suggests that the characteristic time scale for the evolution of global weather patterns is approximately one day. From Crossfield et al. (2014, Figure 2), by permission from Nature/Springer/Macmillan Ltd, ©2005.

LP 944–20 (Rutledge et al., 2000), are now known for a number of objects.

As for M dwarfs, brown dwarfs may also possess detectable radio emission, attributed to cyclotron radiation due to non-relativistic electrons in the coronal plasma (box, page 101). Radio emission was also first detected from LP 944–20 (Berger et al., 2001). An overall detection rate of around 10% for 90 objects of spectral type M5–T8 was given by Berger (2006).

### 9.6.7 Occurrence as binary companions

Of brown dwarfs detected in the imaging surveys such as DENIS, 2MASS, and SDSS, the majority are isolated objects. A small subset, around 5% (Gizis et al., 2001, 2002), have also been detected in these surveys as wide common proper motion companions of nearby main sequence stars.

Probing their occurrence as companions to normal stars at smaller angular separations has been addressed by direct imaging, radial velocity, and astrometric surveys – including as by-products in the search for planets. One brown dwarf–brown dwarf eclipsing binary pair has been reported (Stassun et al., 2006).

Imaging surveys have targeted mainly nearby objects ( $\leq 50$  pc) to maximise the angular separation, and/or young stars ( $\leq 300$  Myr) to enhance the prospects of finding more luminous companions. Surveys have used a combination of coronagraphy (e.g. Oppenheimer et al., 2001), HST (e.g. Brandner et al., 2000; Lowrance

et al., 2005), and ground-based adaptive optics (e.g. McCarthy & Zuckerman, 2004; Neuhäuser & Guenther, 2004; Carson et al., 2005).

Overall, for the orbital separation range 0–3 au, these surveys have confirmed the ‘brown dwarf desert’, originally found from radial velocity observations, where only  $\leq 0.5\%$  of FGK dwarfs are found to have brown dwarf companions (Marcy & Butler, 2000). At orbital separations 10–1000 au, the occurrence rate rises by a factor 5–10 to reach a fraction of 2–4% (Neuhäuser & Guenther, 2004). Beyond separations of 1000 au, the frequency of brown dwarf companions to 2MASS stars is consistent with the frequency of stellar secondaries, at around 18%. The brown dwarf desert is considered further in Section 2.10.5).

Taken together with the results of radial velocity surveys for stellar binaries, there is a strong preference for near-equal mass stellar systems to exist at small physical separations, presumably reflecting the effects of competitive accretion during the star formation process. Wide systems,  $\geq 100$  au, originate from the gravitational association of independent stellar cores, and consequently span a greater range of mass ratios.

## 9.7 Formation of brown dwarfs

Brown dwarfs are roughly twice as numerous as main-sequence stars, although contributing no more than  $\sim 15\%$  to the total local disk mass. This conclusion was already reached by Reid et al. (1999), who represented the density of L dwarfs as a power-law mass function  $\psi(M) \propto M^{-\alpha}$ , with  $1 < \alpha < 2$ . With their results favouring a value nearer to the lower limit, adopting  $\alpha = 1.3$  implies that the local space density of  $10 - 78 M_J$  brown dwarfs is of order  $0.1 \text{ pc}^{-3}$ .

That brown dwarfs are comparable in number to hydrogen-burning stars implies that a robust theory of star formation should also explain their origin. The problem with models attributing their formation to the same process as for Sun-like stars, viz. collapsing molecular cloud cores, has been that the mass of brown dwarfs is some two orders of magnitude smaller than the average Jeans mass in star-forming clouds. If the average Jeans mass sets an approximate lower limit to the stellar mass (Larson, 1992; Adams & Fatuzzo, 1996; Padoan et al., 1997; Elmegreen, 1999), the existence of a significant population of brown dwarfs becomes problematic.

**Turbulent fragmentation** Padoan & Nordlund (2002, 2004) showed that supersonic turbulence in molecular clouds can generate a complex density field with very large density contrasts, with higher densities resulting in a lower Jeans mass (Equation 10.1). In simulations, a fraction of brown dwarf mass cores formed by turbulent flow are dense enough to be gravitationally unstable.

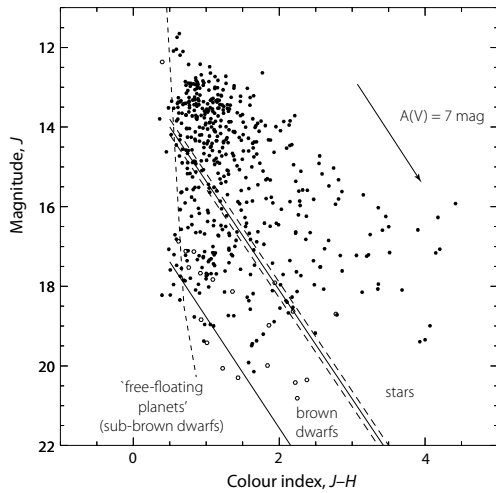


Figure 9.7: Young brown dwarfs and sub-brown dwarfs ('free-floating planets') in Orion, in the colour–magnitude diagram ( $J$  versus  $J - H$ ). Open circles are uncertain data points. The dotted line is an approximate zero-reddening track. Solid lines, parallel to the  $A(V) = 7$  reddening vector, divide the population into stars, brown dwarfs and planet mass, using the predictions of Burrows et al. (1997) and an age of 1 Myr. Dashed lines correspond to 0.3 Myr and 2 Myr, indicating effects of an age spread on the classification. The effect is similar to the planetary boundary. From Lucas & Roche (2000, Figure 1a), © Oxford University Press.

Based on the density, temperature, and Mach number typical of cluster-forming regions, Padoan & Nordlund (2004) propose that star formation by turbulent fragmentation can also account for the observed brown dwarf and sub-brown dwarf abundances. Specifically, they found a good match to the distribution of stellar and substellar members of the young cluster IC 348 determined by Luhman et al. (2003).

More recent and more general work seems to confirm this picture (Hennebelle & Chabrier, 2008, 2009; Luhman, 2012; Hopkins & Christiansen, 2013; Hopkins, 2013; Chabrier et al., 2014).

**Other processes** Other mechanisms proposed to explain the existence and abundance of brown dwarfs rely either on forming a high gas density (and thus a low Jeans mass) in the pre-stellar cores (as in turbulent fragmentation), or on the halting of accretion once a low-mass fragment has formed. Multiple cloud fragmentation during collapse (Burkert et al., 1997), or core accretion followed by the capture of gas in protostellar disks (Bodenheimer, 1998), tend to form a gravitationally bound multiple system, requiring efficient mechanisms to rapidly disrupt the resulting orbits.

**Details** Plausible formation processes have been reviewed by Whitworth et al. (2007), and include (a) hierarchical fragmentation (Boss et al., 2000; Whitehouse & Bate, 2006); (b) disk fragmentation in which a massive circumstellar disk is unstable to

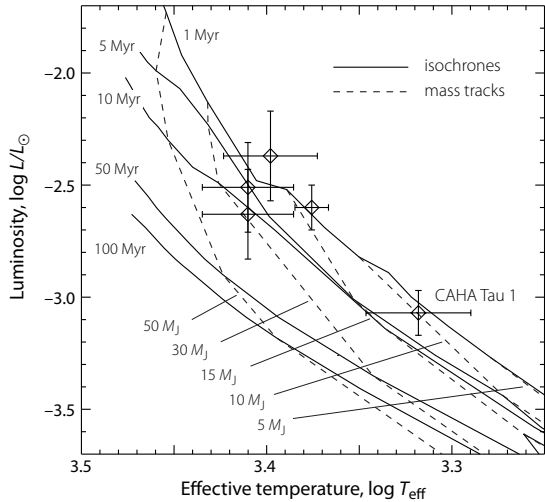


Figure 9.8: Hertzsprung–Russell diagram illustrating the location of some of the low-mass members of the Taurus star-forming region, all with spectral types  $\geq M9.0$ . Luminosities are derived using bolometric corrections, and a reddening  $A_V = 2.3$  mag. Isochrones and mass tracks are from Chabrier et al. (2000). Assuming that the candidates are cluster rather than background objects, CAHA Tau 1 falls between the 1–5 Myr isochrones and, depending on age, its properties translate into a mass between 5–15  $M_J$ . From Quanz et al. (2010a, Figure 10), by permission of IOP Publishing/AAS.

gravitational fragmentation, potentially induced by a stellar fly-by (Bate et al., 2002; Matzner & Levin, 2005; Whitworth & Stamatellos, 2006; Clarke et al., 2007; Goodwin & Whitworth, 2007; Stamatellos et al., 2007; Whitworth et al., 2007), with Goodwin & Whitworth (2007) suggesting that brown dwarfs are formed in disks beyond 100 au, with the resulting binaries being disrupted by passing stars; (c) gravitational fragmentation of infalling filamentary gas into stellar clusters (Bate et al., 2002; Bonnell et al., 2008); (d) the ejection of newly-formed fragments or stellar embryos in multiple systems or circumbinary disks, halting post-formation accretion such that the fragment retains a low mass (Boss, 2001; Reipurth & Clarke, 2001; Smith & Bonnell, 2001; Bate et al., 2002; Kroupa & Bouvier, 2003; Jiang et al., 2004; Bate & Bonnell, 2005; Basu & Vorobyov, 2012); and (e) the photoevaporation of a collapsing pre-stellar core, for example through the wind of nearby supernovae or OB stars (Whitworth & Zinnecker, 2004; Gahm et al., 2007).

## 9.8 Disks, outflows, and planets

Just as many stars are orbited by protoplanetary disks and planets, there are growing numbers of brown dwarfs themselves known to be orbited by dust disks, as well as lower-mass planetary-type companions.

### 9.8.1 Disks around brown dwarfs

It is now known that disks around young brown dwarfs are relatively common. Although difficult to image directly, details of their existence, sizes, and masses can be inferred from their infrared excess and their detailed

spectral energy distributions. Outwards from the central body, the decreasing disk temperature means that characterising the dust benefits from observations in the mid-infrared (e.g. Spitzer and WISE), far-infrared (e.g. Herschel), and sub-mm (e.g. ALMA) respectively.

The nearest star forming regions ( $\tau \sim 0.5 - 3$  Myr,  $d = 150 - 300$  pc) have proven to be well suited for these investigations, especially those surveyed extensively for brown dwarfs, such as IC 348, Cha I, and Taurus (§9.2.4).

The current observational picture is that brown dwarfs often have substantial disks, with sufficient material from which Earth or Neptune mass planets might be formed. Characterising the disks, including measuring the mass range over which brown dwarfs host circumstellar disks, is important both for understanding brown dwarf formation, and for determining whether planets can form around low-mass brown dwarfs.

**Early evidence** Early indirect spectroscopic evidence for brown dwarf circumstellar disks was seen in accretion signatures, notably via the presence of broad H $\alpha$  emission, as observed in GM Tau, IC 348–382, and others (e.g. White & Basri, 2003; Muzerolle et al., 2003; Jayawardhana et al., 2003b; Mohanty et al., 2003).

More direct evidence was provided by the detection of infrared emission at levels above that expected only from a stellar photosphere. Modest excess emission in  $K$  and  $L$  was first observed for several young objects of spectral type M6–M8 (e.g. Luhman, 1999; Lada et al., 2000; Muench et al., 2001; Liu et al., 2003a; Jayawardhana et al., 2003a; Lada et al., 2004; Luhman, 2004).

Collectively, these early results indicated that disks around young brown dwarfs are relatively common.

**Far infrared and sub-mm observations** At longer wavelengths, mid-infrared excesses were detected with ISO (e.g. Comerón et al., 1998, 2000; Persi et al., 2000; Natta & Testi, 2001), and subsequently with Gemini (Apai et al., 2004b; Sterzik et al., 2004).

Disk observations have since been made with Spitzer-IRAC, including OTS 44, the coolest and least massive known brown dwarf in the Cha I star-forming region (Luhman et al., 2005b), Cha 110913–773444 (Luhman et al., 2005a), planetary mass objects in  $\sigma$  Ori (Zapatero Osorio et al., 2007; Luhman et al., 2008b), Cha I (Luhman & Muench, 2008), 2M J04442713+2512164 (Bouy et al., 2008), and  $\rho$  Oph (Harvey et al., 2010).

Similar observations have also been made with WISE (e.g. Riaz et al., 2012b).

Observations at mm wavelengths were first reported for CFHT-BD-Tau 4 and IC 348–613 with JCMT and IRAM (Klein et al., 2003). The combination of these mid-infrared and (sub-)mm observations provided the first comprehensive spectral energy distribution of the circumstellar material around the young brown dwarf CFHT-BD-Tau 4 (Pascucci et al., 2003).

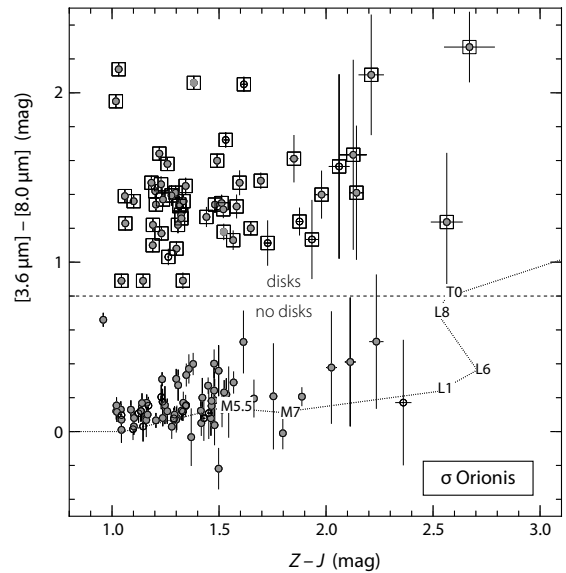


Figure 9.9: VISTA and Spitzer-IRAC  $[3.6 \mu\text{m}] - [8.0 \mu\text{m}]$  versus  $Z - J$  colour-colour diagram of all VISTA sources in the  $\sigma$  Ori cluster with data available in the four filters. Filled circles are confirmed cluster members, open circles are unconfirmed. Objects with significant flux excesses at  $8 \mu\text{m}$  (framed circles) lie above the horizontal dashed line, taken as the separator between objects with and without surrounding disks. The average location of early-M to T0 field dwarfs is shown by the dotted line, with spectral types labeled. Sources without infrared flux excesses follow the field sequence. From Peña Ramírez et al. (2012, Figure 4), by permission of IOP Publishing/AAS.

Far infrared and (sub-)mm observations have continued with the Herschel space observatory and ALMA.

Herschel (Pilbratt et al., 2010) was operational between 2009–2013, with instruments sensitive to the far infrared and sub-mm ( $55\text{--}672 \mu\text{m}$ , Poglitsch et al., 2010; Griffin et al., 2010).

ALMA provides imaging in all atmospheric windows between  $350 \mu\text{m}$  and  $10$  mm. It began observations in 2011, and has been fully operational since March 2013 (§3.11.2).

**Disk frequency** Out of 210  $\sigma$  Ori member candidates detected with VISTA, and with masses in the range  $0.25\text{--}0.004 M_{\odot}$  ( $250 - 4 M_J$ ), comprising 104 very low mass stars, 69 brown dwarfs, and 37 planetary mass objects, 128 were detected in the IRAC-Spitzer  $3.6$  and  $8.0 \mu\text{m}$  bands, of which 54 have a colour  $[3.6] - [8.0] \geq 0.8$  mag. Peña Ramírez et al. (2012) identified these as objects harbouring disks, yielding a (probable lower limit to the) global disk fraction of 42%, with no evident dependent on mass or cluster location (Figure 9.9).

**Disk masses** Disk masses have been measured for a number of young brown dwarfs through far-infrared and sub-mm photometry, assuming optically thin emission and an ISM-like dust-to-gas mass ratio (Klein et al., 2003;

Scholz et al., 2006; Harvey et al., 2012a; Ricci et al., 2012b, 2014). Because of the degeneracy between disk radius and surface density and geometry, photometry alone does not provide strong constraints on the radial distribution of mass in the disk.

Herschel observations of 47 M3–M9.5 brown dwarfs, with ages 1–10 Myr, and in a variety of star forming environments (Harvey et al., 2012b,a) yielded 36 detected at 70  $\mu\text{m}$ , and 14 at 160  $\mu\text{m}$ , a range of 24–70  $\mu\text{m}$  colours suggesting a range in mass and/or structure of the outer disk, and a wide range in total disk masses from less than  $10^{-6} - 10^{-3} M_{\odot}$  with a median of  $3 \times 10^{-5} M_{\odot}$ .

For the low-mass M9.5 brown dwarf OTS 44, VLT-SINFONI spectroscopy has shown that significant accretion and substantial disks can occur down to host masses as low as  $12 M_{\text{J}}$  (Joergens et al., 2013a), with ALMA providing further disk properties (Bayo et al., 2017).

**Disk radii and structures** A direct observational estimate of the radius of a disk around a single young brown dwarf was made for the nearly edge-on disk around 2M J0438+2611, where combined Spitzer spectroscopy and high-angular resolution HST imaging yielded a disk radius of about 20–40 au from the optical images of the disk in scattered light (Luhman et al., 2007a). Observations of the young brown dwarf 2M J0444+2512 in the Taurus molecular cloud have been made with the CARMA interferometer at 1.3 mm, similarly yield a disk radius in the range 15–30 au (Ricci et al., 2013), and with the VLA (Ricci et al., 2017c).

ALMA is providing further constraints on disk structures. For three young brown dwarfs in Taurus, Ricci et al. (2014) found that the disks are relatively large (the smallest of radius  $\sim 70$  au), with radii, radial profiles of dust surface density, and disk-to-central object mass ratios lying within the ranges found for disks around more massive young stars. In all three, data are consistent with the presence of grains of at least mm size, again confirming that the early stages of the solid growth toward planetesimals occur also around very low mass objects.

Testi et al. (2016) surveyed 17 young brown dwarfs in the  $\rho$  Oph star-forming region, detecting continuum emission in 11 (65%), with an inferred dust/disk mass in the range  $0.5 - 6 M_{\oplus}$ , and sharp (truncated) outer edges at  $R \lesssim 25$  au in two. The low disk masses imply that planet formation around brown dwarfs may be relatively rare, and that the supra-Jupiter mass companions found around some brown dwarfs are probably the result of a binary system formation.

**Other effects** Post-encounter disk properties in triple systems have been considered by Umbreit et al. (2011).

### 9.8.2 Jets and outflows

**Comparison with classical T Tauri stars** Star formation involves not only accretion, but also the expulsion

of matter in the form of supersonic outflows and jets (e.g. Ray et al., 2007; Machida et al., 2009). Such outflows, which originate in the radiative cooling zones with moderate- to large-velocity shocks, have been observed for many classical T Tauri stars.

Detections have been made through narrow-band emission-line imaging, or through spectro-astrometry. The latter recovers spatial information below the telescope's diffraction limit through variations in the positional centroid of the emission as a function of wavelength. The development of spectro-astrometry applied to classical T Tauri stars (Solf, 1984; Solf & Boehm, 1993; Hirth et al., 1994, 1997), eventually led to the resolution of jets at 10 au distance from the central source (e.g. Garcia et al., 1999; Takami et al., 2001, 2003).

The observed correlation between mass outflow and disk accretion indicates a magnetohydrodynamic jet-launching mechanism (Joergens et al., 2012). The jet could originate from either a wide range of disk radii (the 'disk wind model'), as favoured by kinematic and collimation studies of [Fe II] emission in DG Tau (Agra-Amboage et al., 2011), or at the interface between the stellar magnetosphere and the disk (the 'X wind model').

Typical mass-loss rates for classical T Tauri stars are  $\sim 10^{-9} - 10^{-7} M_{\odot} \text{ yr}^{-1}$ , some 5–10% of the mass accretion rate (e.g. Sicilia-Aguilar et al., 2006, 2010; Fang et al., 2009). The fact that some jets have been found to rotate (e.g. Launhardt et al., 2009) furthermore suggests that jets may also transport a significant amount of angular momentum from the accretion disk.

**Outflows in brown dwarfs** During their early evolution, brown dwarfs resemble higher mass T Tauri stars in many of their properties (Joergens et al., 2013b). Very young brown dwarfs (a few Myr) display chromospheric activity, such as surface spots (e.g. Joergens et al., 2003). Many of the brown dwarf disks, inferred from their mid-infrared and far-infrared/submm excess emission ( $\text{\$9.8.1}$ ) are found to be actively accreting (e.g. Mohanty et al., 2005; Herczeg & Hillenbrand, 2008; Bacciotti et al., 2011; Rigliaco et al., 2011), while several show signs of grain growth and crystallisation (e.g. Apai et al., 2005; Pascucci et al., 2009). Very young brown dwarfs rotate on average much slower (e.g. Joergens & Guenther, 2001; Joergens et al., 2003; Caballero et al., 2004) than their older counterparts (e.g. Bailer-Jones & Mundt, 2001; Mohanty & Basri, 2003), suggestive of a magnetic braking mechanism due to interaction with the disk.

The first indication that brown dwarfs and very low-mass stars might also drive T Tauri-like outflows came from the observation of forbidden emission in the spectrum of the actively accreting M6.5 dwarf LS-R CrA 1 (Fernández & Comerón, 2001).

Spectro-astrometry of [N II], [O I], and [S II] in several brown dwarfs and very low mass stars subsequently confirmed that objects in the mass range  $0.1 M_{\odot}$  to  $\lesssim 30 M_{\text{J}}$



can generate powerful outflows, as observed for  $\rho$  Oph-102 (M5.5, Whelan et al., 2005); 2M J1207-3932 (M8, 24  $M_J$ , Whelan et al., 2007, 2012); LS-R CrA 1 (M6.5, Whelan et al., 2009a); Par-Lup3-4 (M5, Bacciotti et al., 2011); ISO Cha I-217 and ISO Oph-32 (M8, Bacciotti et al., 2011); and ISO-217 (Joergens et al., 2012), and Mayrit 1701117 and Mayrit 1082188 in  $\sigma$  Ori (Riaz et al., 2015).

This was further supported by resolved imaging of the outflow of the very low-mass star  $\rho$  Oph-102 (M5.5), detected in the CO J=2-1 transition, and showing a 10 arcsec offset from the central source (Phan-Bao et al., 2008b, 2011). Directly resolving brown dwarf outflows in forbidden emission lines is more challenging because their critical density occurs at very close separations, of  $\sim 100$  mas at  $d \sim 150$  pc (e.g. Wang & Henning, 2006).

Estimates of the mass-loss rates of these objects gives  $\dot{M}_{\text{out}} = 10^{-9} - 10^{-10} M_{\odot} \text{ yr}^{-1}$  (Whelan et al., 2009b; Bacciotti et al., 2011). A comparison with mass accretion rates for brown dwarfs,  $\dot{M}_{\text{acc}} = 10^{-9} - 10^{-11} M_{\odot} \text{ yr}^{-1}$  (e.g. Muzerolle et al., 2003; Natta et al., 2004; Mohanty et al., 2005; Herczeg & Hillenbrand, 2008) gives tentative hints of a relatively high  $\dot{M}_{\text{out}}/\dot{M}_{\text{acc}}$  ratio, reaching 40% for Par-Lup3-4 (Bacciotti et al., 2011).

Molecular outflows have also been observed in brown dwarf or proto-brown dwarf candidates at sub-mm wavelengths (Phan-Bao et al., 2008b; Monin et al., 2013; Palau et al., 2014; Phan-Bao et al., 2014a,b).

A few very low luminosity objects have been detected at cm wavelengths (André et al., 1999; Shirley et al., 2007; Palau et al., 2012).

**Proto-brown dwarfs** Observations of *proto-brown dwarfs* (Morata et al., 2015), deeply-embedded brown dwarfs equivalent to the Class 0/I stage of low-mass young stellar objects (André et al., 1993), offer the prospect of testing the turbulent fragmentation scenario for brown dwarf formation (§9.7), by comparing their properties to those of low-mass protostars.

For a sample of 12 proto-brown dwarf candidates, identified from Spitzer colour-colour and colour-magnitude diagrams (Barrado et al., 2009; Palau et al., 2012), observations at 3.6 and 1.3 cm with the Jansky VLA have detected thermal radio jets in about half the cases (Morata et al., 2015). Their results, and modeled outflow rates (Figure 9.10), support the idea that their formation mechanism is indeed a scaled-down version of that of low-mass stars.

Other candidate proto-brown dwarfs have since been reported, including L328-IRS (Lee et al., 2013b) and IC348-SMM2E (Palau et al., 2014).

### 9.8.3 Planets around brown dwarfs

Other brown dwarfs are now known to be orbited by ‘planets’, amongst them 2M J1207 (Chauvin et al., 2005a) and 2M J0441 (Todorov et al., 2010b), both detected by

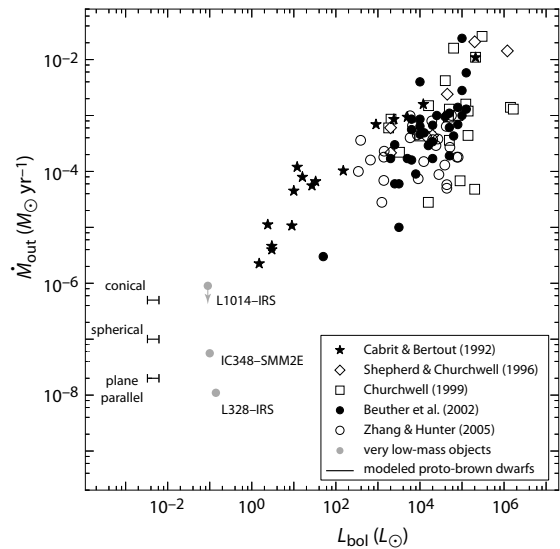


Figure 9.10: Mass outflow rate,  $\dot{M}_{\text{out}}$ , versus bolometric luminosity,  $L_{\text{bol}}$ , for the young stellar objects referenced. Grey circles are the very low mass object L1014-IRS (Shirley et al., 2007), and two very young proto-brown dwarfs, IC348-SMM2E (Palau et al., 2014) and L328-IRS (Lee et al., 2013b). Horizontal bars indicate  $L_{\text{bol}}$  for the proto-brown dwarfs powering the thermal radio jets detected by Morata et al. (2015), and their three different modeled values of  $\dot{M}_{\text{out}}$  (their Section 4.3). From Morata et al. (2015, Figure 8), by permission of IOP Publishing/AAS.

direct imaging (§7.10). An unsuccessful search for transiting planets orbiting 44 nearby brown dwarfs, from Spitzer archival data, was reported by He et al. (2017b).

Predicted properties of an optical transient event resulting from a planet-brown dwarf merger have been considered by Bear et al. (2011a).

**Habitable planets around brown dwarfs** Being close to their host star, the habitable zones of nearby brown dwarfs are interesting candidates for follow-up occultation spectroscopy of potentially transiting habitable planets, and those with an orbital period shorter than 8-10 h could be fully monitored over a single night (Belu et al., 2013). From a simulated survey of 21 brown dwarfs within 7 pc, Belu et al. (2013) found that the probability of detecting at least one transiting habitable planet is around 5-50%. They estimate that brown dwarfs within 5-10 pc can be characterised for potential biosignatures with a 6.5-m space telescope using  $\sim 1\%$  of a 5-year mission lifetime.

### 9.8.4 Disk/planet formation around brown dwarfs

The leading mechanisms proposed for the formation of brown dwarfs also produce substellar objects that are surrounded by disks, albeit with different disk fractions (e.g. Stamatellos & Herczeg, 2015).

Planet formation in protoplanetary disks, which is marked by growth and crystallisation of sub- $\mu\text{m}$  dust grains to mm-sizes, accompanied by settling towards the disk mid-plane, also appears to take place in a sim-

ilar manner in these very low mass brown dwarf disks (Apai et al., 2005; Payne & Lodato, 2007; Apai, 2013).

Pinilla et al. (2013) simulated dust growth and evolution using models of coagulation, fragmentation, and disk-structure, finding that fragmentation is less likely and rapid inward drift more significant than in T Tauri disks. A model fitting the mm disk fluxes included strong pressure inhomogeneities, small radial extent ( $\sim 15$  au), and moderate turbulence,  $\alpha_{\text{turb}} = 10^{-3}$ .

Meru et al. (2013a) used the model developed by Garaud et al. (2013), which simulates the local coagulation and fragmentation of dust aggregates, to determine the evolution of the particle size distribution function. Each particle's velocity is modeled using a probability density function, but treating the deterministic (i.e., directional) and stochastic (i.e., non-directional) velocities separately. The underlying assumption is that collisions with velocities lower than the bouncing velocity,  $v_b$ , result in sticking, while those with velocities higher than the fragmentation velocity,  $v_f$ , break apart if their mass ratio is smaller than a particular value (the *mass transfer parameter*) and coagulate if it is larger.

Physically this means that collisions between unequal-sized aggregates more likely to lead to growth, while equal-sized aggregates more likely fragment, corresponding to the results from laboratory experiments (Wurm et al., 2005; Teiser & Wurm, 2009), as well as from simulations (Meru et al., 2013b). The initial particle size distribution is a Gaussian centred around  $1 \mu\text{m}$  with a width of  $0.1 \mu\text{m}$ , and simulations proceed until the largest particle size reaches a steady state (some 3.5 times longer for a T Tauri disk than for a brown dwarf disk). Their results suggest that growth can proceed to similar sizes at equivalent locations with respect to the truncation radii in brown dwarf and T Tauri disks, if the former are scaled-down versions of the latter.

## 9.9 Free-floating objects

The terms 'free-floating objects' and 'free-floating objects of planetary mass' have been used to describe at least two different categories of objects, with very different formation histories: objects formed as a by-product of the regular star formation process, and objects originating as part of the planet formation process.

At the present time, evidence for the former is compelling, while evidence for the existence of the latter remains circumstantial. Whatever their origin, microlensing surveys, especially from space, offer good prospects for their identification (§5.3.11).

### 9.9.1 By-products of regular star formation

The first category of objects loosely classified as 'free floating' are the low-mass objects formed as a by-product of regular star formation, perhaps via turbulent

fragmentation, and simply representing the low-mass tail of the relevant mass function (§9.7).

For this type of object the term 'sub-brown dwarf' may be more appropriate (box, page 431). They have also been referred to as 'planemos' (for planetary mass objects, e.g. Scholz et al., 2012a), as 'micro brown dwarfs' (Schild et al., 2012), as 'cluster planets', and, in the form of pre-collapse small opaque dust clouds, as globulettes (Gahm et al., 2013; Haworth et al., 2015).

**Searches in young systems** Searches for isolated objects of (sub-)brown dwarf or planetary mass have focused on star-forming regions and young clusters. As a result of their passive cooling, isolated substellar objects at an age of only a few Myr are then some three orders of magnitude more luminous than those with ages of a few Gyr. Once detected photometrically, masses can be derived from a comparison of the observed luminosity, or observed temperature, with theoretical evolutionary tracks, although complicated by extinction (e.g. Burrows et al., 1997). Their multiplicity and kinematics would provide further constraints on formation processes (Li et al., 2015, 2016c).

Although the lower mass limit for bodies formed by fragmentation of collapsing interstellar gas clouds is uncertain, the mass functions observed in various star-forming regions gave the first indications that isolated objects down to planetary mass could form as a by-product of star formation. These included Orion, Taurus and Chamaeleon (Tamura et al., 1998; Oasa et al., 1999; Lucas & Roche, 2000; Hillenbrand & Carpenter, 2000), and young open clusters including  $\sigma$  Ori and IC 348 (Béjar et al., 1999; Najita et al., 2000; Ansdell et al., 2017).

**Examples** Reports of 'free-floating objects' down to masses of some  $4 - 7M_J$  or lower, have come from deep optical and near-infrared imaging of various regions, including the Chamaeleon I dark cloud at 160 pc (Tamura et al., 1998; Oasa et al., 1999; Luhman et al., 2008a; Esplin et al., 2017); the Trapezium cluster in Orion (Lucas & Roche, 2000; Lucas et al., 2001, 2005, 2006; Weights et al., 2009; Andersen et al., 2011); the Taurus star-forming region (Quanz et al., 2010a); the  $\sigma$  Ori cluster at 440 pc (Zapatero Osorio et al., 2000; Martín et al., 2001b; Bihain et al., 2009; Peña Ramírez et al., 2012; Zapatero Osorio et al., 2017); the AB Dor moving group (Delorme et al., 2012a; Naud et al., 2017a); the Rosette nebula (Gahm et al., 2013); the 32 Ori moving group (Burgasser et al., 2016); and the TW Hya association (Kellogg et al., 2016; Gagné et al., 2017).

The first reported examples, with  $\{M_p/M_J, T\}$  include S Ori 68 {5, -} (Zapatero Osorio et al., 2000), S Ori 70 {3, 1100} (Zapatero Osorio et al., 2002), Cha 110913 {8, 1350} (Luhman et al., 2005a), CAHA Tau 1 {10, 2080} (Quanz et al., 2010a), CAHA Tau 2 {11.5, 2280} (Quanz et al., 2010a), and  $\rho$  Oph 4450 {2 - 3, 1400} (Marsh et al., 2010). Again, current findings suggest that these formed as the low-mass tail of star formation, and there is no evidence to suggest (neither is it claimed) that they have been ejected from planetary systems.

Planetary-mass brown dwarf binaries, such as the  $14M_J - 7M_J$  binary Oph 162225-240515 (Jayawardhana & Ivanov, 2006) have also been observed. The formation of such a wide (240 au) low-mass binary may pose a challenge to formation models, although re-capture processes have also been invoked (§9.9.2).

**Mass spectrum** Masses may extend down to  $\sim 3M_J$  in the case of  $\rho$  Oph 4450 (Marsh et al., 2010) and S Ori 70 (Zapatero Osorio et al., 2002; Martín & Osorio, 2003), although the cluster

membership and hence the mass of the latter were challenged by Burgasser et al. (2004). Masses extend down to  $\sim 5-6M_J$  in the case of NGC 1333, with 3 confirmed objects having  $< 15M_J$ , and the total number of such low mass objects in the cluster estimated to be  $\lesssim 8$  (Scholz et al., 2012a).

The mass spectrum in NGC 1333 is well approximated by  $dN/dM \propto M^{-\alpha}$  with  $\alpha = 0.6 \pm 0.1$  for  $M < 0.6M_\odot$  (Scholz et al., 2012a). A similar result is found for  $\sigma$  Ori (Peña Ramírez et al., 2012), with  $\alpha = 1.7 \pm 0.2$  for  $M > 0.35M_\odot$ , and  $\alpha = 0.6 \pm 0.2$  for  $M < 0.35M_\odot$ , extending smoothly down to  $0.004M_\odot \sim 4M_J$ .

**Star to sub-brown dwarf continuum** The continuum of properties between stars, brown dwarfs, and the suggested ‘free-floating planets’ are evident in Figure 9.7. An example of the Hertzsprung–Russell diagram ( $L$  versus  $T_{\text{eff}}$ ) used to estimate masses from theoretical evolutionary models is shown in Figure 9.8. These observations suggest that the formation of brown dwarf and planetary mass objects are relatively abundant at least in some young clusters (e.g. Lodieu et al., 2008; Quanz et al., 2010a, and references), although not in all (Lyo et al., 2006). They also imply that the formation of unbound planetary mass objects is completed within a few Myr.

Whether these objects are truly isolated was probed by the  $\sigma$  Ori cluster survey by Caballero et al. (2006). They discovered a M5–6 brown dwarf of  $45M_J$  at a separation of 4.6 arcsec (1700 au) from S Ori 68. Such a wide separation is reminiscent of the brown dwarf–planet pairs 2M J1207 at 55 au (Chauvin et al., 2005a), GQ Lup at 100 au (Neuhäuser et al., 2005; Schwarz et al., 2016a), and AB Pic at 250 au (Chauvin et al., 2005b).

In young clusters, planetary mass objects have a similar location in the HR diagram to older and more massive brown dwarfs. Age estimates in turn affect determination of the substellar initial mass function. Canty et al. (2013) demonstrated that the gravity-sensitive  $2.21 \mu\text{m}$  Na I doublet, as well as the shape of their  $K$ -band spectra, correlate with age, allowing a statistical discrimination over the age range 1–10 Myr.

### 9.9.2 Ejected planets and nomads

The second category of ‘free-floating objects’ embraces objects which would have formed as planets in regular planetary systems, and which were subsequently ejected (becoming gravitationally unbound) through a variety of (postulated) processes noted below. Ejected planets are also variously described as ‘unbound planets’, ‘rogue planets’ (e.g. Abbot & Switzer, 2011), or ‘escapes’ (Schild et al., 2012).

Although none have yet been securely identified, they are widely predicted to exist as a result of ejection or escape from their host planetary system by a variety of dynamical processes. These processes include:

- *planet–planet scattering*, resulting from planet–planet interactions within a planetary system (§10.10.4).
- *star–planet scattering*, resulting from stellar fly-bys and in particular in clusters prior to dispersal (§10.10.5).
- *ejection following stellar mass loss*, and particularly during late stellar evolutionary phases (§10.9.4).

**Nomads** Strigari et al. (2012) hypothesise a still larger class of free-floating low mass bodies, say with masses between those of Jupiter and Pluto, plausibly expected

from present models of protoplanetary disk dispersal and planet formation. They refer to them as *nomads*, of which free-floating planets would be a sub-class.

**Detectability from direct imaging** Pacucci et al. (2013) estimated that 26% of stars in the Pleiades cluster might have lost their planets. Assuming planet surface temperatures of 500 K, Pacucci et al. (2013) estimate that a free-floating Pleiades Jupiter would have a specific flux  $F_V \sim 4 \times 10^2$  nJy at  $4.4 \mu\text{m}$ , implying detectability with JWST at  $S/N \sim 100$  in 1 h.

**Constraints from microlensing** Constraints on the numbers of free-floating (including ejected) planets comes from microlensing observations, which has suggested a substantial population,  $\sim 1.8_{-0.9}^{+1.3}$  per star, of apparently free-floating planets (Sumi et al., 2011), although some of these may have host stars too faint to be resolved or too far away (see also §5.10.2).

Veras & Raymond (2012) used N-body simulations to demonstrate that such a number would exceed the plausible number of ejected planets per system from planet–planet scattering. Thus, other potential sources of free floaters, such as planetary stripping in stellar clusters and post-main-sequence ejection, would need to be invoked if this population is confirmed.

The findings that planetary mass objects (5–15 $M_J$ ) in NGC 1333 are some 20–50 times less numerous than stars (Scholz et al., 2012a) also appears to be in conflict with this microlensing-inferred population. If both results are confirmed, the microlensing free-floating planets must have a different origin from the brown dwarfs and planetary mass objects observed in young clusters.

Whatever their origin, microlensing surveys offer good prospects for improving these constraints in the future (§5.3.11). Strigari et al. (2012) estimated that WFIRST could measure the number of nomads per main sequence star  $> 1M_J$  to 13%, and the corresponding number  $> M_{\text{Mars}}$  to 25%, with all-sky surveys such as Gaia and LSST capable of identifying nomads  $\geq 1M_J$ .

**Re-capture of free-floating planets** Some exoplanet systems are observed to have massive planets orbiting their host stars in wide orbits, at some hundreds of au from their host star. These include planets orbiting various members of the 5 Myr old Upper Sco association: 1RXS J160929.1–210524 (Lafrenière et al., 2008; Ireland et al., 2011), GSC 06214–00210 (Ireland et al., 2011), and HIP 78530 (Lafrenière et al., 2011).

Such systems are not easily produced in current models of planet formation, and their origin is specifically debated (e.g. Veras et al., 2009; Dodson-Robinson et al., 2009; Boss, 2011b; Kratter et al., 2010b).

One mechanism suggested to explain their existence is via the re-capture of some of the free-floating planets liberated by stellar interactions in dispersing stellar clusters, in both single and binary stars (Perets &

Kouwenhoven, 2012; Parker & Quanz, 2012; Goulini & Ribak, 2018). Such a mechanism has also been postulated to explain the existence of (some) wide stellar binaries (Kouwenhoven et al., 2010; Moeckel & Bate, 2010; Moeckel & Clarke, 2011), and possibly the Oort cloud (Levison et al., 2010).

Perets & Kouwenhoven (2012) found that this mechanism can also produce free-floating planet–planet binaries, planetary-mass brown dwarf binaries (such as Oph 162225–240515; Jayawardhana & Ivanov, 2006), as well as planetary systems around compact objects such as white dwarfs and black holes.

Varvoglis et al. (2012) give the probability of capture as a function of the planet’s mass, finding both prograde as well as retrograde captured orbits, as well as captured orbits which are tight and highly eccentric.

**Habitability** Habitability of ejected planets has also been considered (Abbot & Switzer, 2011; Badescu, 2011). Abbot & Switzer (2011) estimated that such a planet of Earth-like composition and age could maintain a subglacial liquid ocean for  $M \sim 3.5M_{\oplus}$ , corresponding to  $\sim 8$  km thickness of ice. Suppression of the melting point by contaminants, a layer of frozen gas, or a larger complement of water could reduce the planetary mass required to maintain a liquid ocean. Such a planet could be detected from reflected solar radiation, and its thermal emission could be characterised in the far-infrared, if it were to pass within 1000 au of Earth.

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# Formation and evolution

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**P**LANETARY SYSTEMS, the solar system amongst them, are believed to form as inevitable and common by-products of star formation. For orientation, an overview of the processes described in this chapter is as follows.

The present paradigm starts with star formation in molecular clouds. Brown dwarfs are formed as the low-mass tail of this process, although some may be formed as a high-mass tail of planet formation. Gas and dust in the collapsing molecular cloud which does not fall directly onto the protostar resides in a relatively long-lived accretion disk which provides the environment for the subsequent stages of planet formation. Terrestrial-mass planets are formed within the disk through the progressive agglomeration of material denoted, as it grows in size, as dust, rocks, planetesimals and protoplanets. A similar process typically occurring further out in the disk results in the cores of giant planets, which then gravitationally accumulate their mantles of ice and/or gas.

As the planet-forming bodies grow in mass, growth and dynamics become more dominated by gravitational interactions. Towards the final phases, and before the remaining gas is lost through accretion or dispersal, the gas provides a viscous medium at least partially responsible for planetary migration. Some migration also occurs during these later stages as a result of gravitational scattering between the (proto-)planets and the residual sea of planetesimals. The final structural stabilisation of the planetary system may be affected by planet–planet interactions, until a configuration emerges which may be dynamically stable over billions of years.

The current observational data for exoplanet systems is broadly compatible with this overall picture. Other constraints come from a substantial body of detailed observations of the solar system (Chapter 12).

## 10.1 Context and present paradigm

An understanding of how planets form is essential in understanding and interpreting the considerable range of observed planetary system architectures and dynamics.

Today, the most widely considered *solar nebula theory* holds that planet formation in the solar system, and

by inference in other exoplanet systems, follows on from the process of star formation and accretion disk formation, through the agglomeration of residual material as the protoplanetary disk collapses and evolves.<sup>1</sup>

In the present paradigm, planet formation proceeds by a ‘bottom-up’ process, with bodies of ever-increasing size being produced. It proceeds through a number of stages characterised by qualitative differences in the respective particle interactions. Together these extend over more than 14 orders of magnitude in size, from the sub-micron dust grains to the giant planets.

### 10.1.1 Historical background

Scientific theories of the formation of the solar system had been under consideration since well before the discovery of exoplanets and circumstellar disks, and even before current theories underlying star formation and protoplanetary disks had been developed. Different theories date back to the works of Emanuel Swedenborg in 1734, the Comte de Buffon in 1749, Immanuel Kant in 1755, and Pierre-Simon Laplace in 1796.

Laplace (1796) considered that gaseous clouds, or nebulae, slowly rotate, gradually collapse and flatten due to gravity, and eventually form stars and planets. In this model, planets formed by detachment of a discrete system of gaseous rings, within which clumps and planets grew by spontaneous gravitational collapse. Laplace’s nebula model was pre-eminent in the 19th century. But it was largely abandoned in the early 20th century because it was unclear how material could be spontaneously partitioned such that the Sun retained 99.86% of the mass of the solar system while the planets ended up with 99.5% of the total angular momentum in their orbital motion.

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<sup>1</sup>The *solar nebula* refers to the gas and dust disk left over from the Sun’s formation. In cosmogenic theories of the solar system, theories of formation are divided into *monistic* or *dualistic* depending on whether the Sun and planets were produced by the same or different processes. The present solar nebula theory is considered monistic.

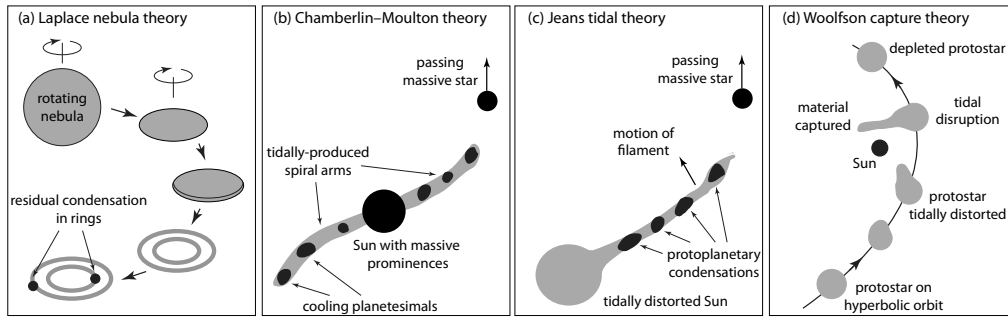


Figure 10.1: Schematic of alternative mechanisms that have been proposed for the formation of the solar system: (a) Laplace nebula theory, in which the rotating nebula collapses, leaving rings of material in which condensations form; (b) Chamberlin–Moulton planetesimal theory, where high-density regions come from solar prominences drawn out by tidal disruption; (c) Jeans tidal theory, where condensations form in ejected filaments from the tidally-distorted Sun; (d) Woolfson capture theory, showing successive configurations of a disrupted protostar leading to captured material. Adapted from Woolfson (1993, Figures 1–4).

Various alternatives were subsequently proposed. These included (Figure 10.1) the idea that planetesimals formed out of material from an erupting Sun (Chamberlin, 1901; Moulton, 1905); a tidal model involving interaction between the Sun and a massive star (Jeans, 1917); the star–Sun collision theory (Jeffreys, 1929a,b); the Schmidt–Lyttleton cloud accretion model (Schmidt, 1944; Lyttleton, 1961); the turbulence-collision driven protoplanet theory (McCrea, 1960, 1988); the tidal capture theory involving the Sun and a low-mass protostar (Woolfson, 1964; Williams & Woolfson, 1983; Dormand & Woolfson, 1989; Woolfson, 2013, 2016); and a modern form of the Laplacian hypothesis (Prentice, 1978a,b).

These and other aspects of earlier and alternative ideas of the formation of the solar system, and a perspective of difficulties faced by the developing solar nebula theory, are discussed by Woolfson (1993, 2000a,b, 2003, 2007). A review of theories developed between 1956–85 is given by Brush (1990).

### 10.1.2 Present paradigm

Planet formation, the clumping of solid material to form the terrestrial planets and the putative cores of gas giants, is generally viewed as taking place in three reasonably distinct stages.

**Three stages of growth** In the first stage, within protoplanetary disks, dust grains of heavy elements that condensed from the cooling gas, and any that survived shocked entry into the protoplanetary nebula, collide and stick by short-range van der Waals attraction. The process is accelerated by turbulence but is still effective in laminar disks, and results in cm or larger particles.

In the second stage of growth, from cm to km-sized bodies, planetesimals (bodies of  $\geq 1$  km, akin to present-day asteroids) somehow form. However, growth by binary accretion becomes problematic in a turbulent nebula due to shattering, and different growth scenarios are

being considered. Details of this stage remain particularly uncertain because of the complicated underlying physics: where and how small bodies aggregate (with collisions, fragmentation, and bouncing), how they interact and migrate with a turbulent gas disk, and on a whole variety of (internal and external) conditions such as disk mass, photoevaporation, ionisation, radiogenic heating, and many others.

The third ‘coagulation’ stage, dominated by gravity, is conceptually more straightforward. Planetesimals merge in a binary manner by physical and/or gravitational capture as they collide. Continued accretion yields protoplanets (embryos or planetary cores) on time scales of  $10^5$ – $10^6$  yr, which continue to collide and merge into full-sized planets.

**Coagulation zones** Three somewhat distinct coagulation zones can be distinguished: (a) in the terrestrial zone, coagulation produces dozens of sub-Earth-sized bodies that undergo a velocity instability once they have accreted half the planetesimals, leading to an epoch of large-scale chaos and giant impacts before settling into a more stable dynamical configuration; (b) just beyond the snow-line, one or more planets may grow to  $\sim 5$ – $10M_{\oplus}$ , enough to capture large amounts of gas as they sweep through the nebula, creating the gas giants with deep atmospheres like those of Jupiter and Saturn; (c) in the asteroid belt, Kuiper belt, and debris disks, coagulation was incomplete, either because the coagulating planetesimals were excited by exterior planets before forming planets themselves, or because the initial surface density was too low.

The primordial phase of disk evolution, when giant planets form, ends with dissipation of the gas. This typically completes in 1–6 Myr, with 3 Myr often cited as a typical lifetime for gaseous disks. Over the next few Myr, the remnant primordial circumstellar dust is either dispersed by stellar radiation, decelerated by Poynting–

Robertson drag and accreted onto the star, destroyed in collisions, or accreted onto growing planetesimals.

Throughout the subsequent ~30 Myr, rocky terrestrial protoplanets continue to accumulate planetesimals, and icy planets accrete icy planetesimals beyond the system's snow line. By 100 Myr, current models portray planetary systems at a relatively mature stage, with little accretion growth occurring. Significant surface evolution and alteration may still occur via impacts, delivery of volatiles, and deposition of a 'late veneer'. Over the next few Gyr of the star's main-sequence life, observable amounts of dust in a debris disk may be created by the steady-state grinding of planetesimals or the occasional large impact.

The solar system planets are, in consequence, the winners of a long series of accretion events, mergers, and violent impacts.

While this present paradigm of planet formation is consistent with a wide range of observations (including the occurrence of protoplanetary, transition, and debris disks, and exoplanet population statistics) various important details remain uncertain (e.g. Chambers, 2004).

In their review of challenges in understanding planet formation, Morbidelli & Raymond (2016) list their top five conceptual 'bottlenecks' as: the structure of protoplanetary disks; the formation of the first planetesimals; details of the speed and direction of migration; the origin of the solar system's tri-modal structure; and the relationship between terrestrial planets and super-Earths.

**Organisation of material** A strictly linear description of the details underpinning planet formation is challenging. Many processes are at work, and many detailed ideas and simulations have been put forward. Some ideas have been superseded or modified, while others have been abandoned by some researchers while remaining under intensive investigation by others.

The approach adopted here is to first present the various conditions and processes which are believed to operate within protoplanetary disks, and in the slightly later stages of transition disks. With this background, a more sequential description of the processes believed to underpin terrestrial planet formation, is followed by the physical processes which determine the morphology and structure of the terrestrial planets. This is followed by the processes believed to control the formation of the giant planets, both the core accretion model, the gravitational disk instability model, and the tidal downsizing model. Models and applications to specific systems are also mentioned in the relevant appendixes.

**How typical is the solar system?** The possibility that the formation of most exoplanet systems differs from that of the solar system, based on the typically smaller semi-major axes known at the time, was considered by Beer et al. (2004a) and later, from the eccentricities and semi-major axes of stellar, brown dwarf, and exoplanet companions of solar-type stars, by Abt (2010).

With considerably more data, the question of how representative is the solar system was revisited by Martin & Livio (2015). They found that the masses and densities of the solar system giants are very typical, as is the age of the solar system. The orbital location of Jupiter is something of an outlier, most likely due to strong selection effects toward short-period (transiting) planets. Solar system eccentricities are relatively small, but still consistent with expectations for an 8-planet system.

The two characteristics of the solar system found to be most special are the lack of super-Earths with periods of days to months (§10.7.3), and the absence of planets inside of the orbit of Mercury. They concluded that systems like the solar system are not expected to be extremely rare.

## 10.2 Star formation

The macrophysics of star formation deals with the formation of systems of stars, ranging from clusters to galaxies. It is the microphysics of star formation that is of most relevance to planet formation: how protostars acquire their mass via gravitational collapse, how the infalling gas loses its magnetic flux and angular momentum, and how the resulting stellar properties are determined by the medium from which they form.

The accepted paradigm for star formation is that gravitational instabilities in molecular clouds of gas and dust grains lead to gravitational collapse, fragmentation, and accretion (e.g. Shu et al., 1987; McKee & Ostriker, 2007; Whitworth & Lomax, 2016), while for relatively massive stars, *competitive accretion* is an alternative (Zinnecker, 1982; Bonnell et al., 1997). Only the aspects most relevant for planet formation are outlined here, while a list of 17 key steps in the current picture are given by McKee & Ostriker (2007, Section 5).

### 10.2.1 Molecular clouds

Molecular clouds are complex structures with wide density and composition variations, whose nature and scales are defined by turbulence. The gas, whose composition can be established from spectroscopy, consists primarily of H<sub>2</sub>, along with H and He atoms and numerous other molecules (CO, CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>O, HCO, CH<sub>3</sub>OH, NH<sub>3</sub>, ...), with more than 150 species detected in the interstellar medium to date (Semenov et al., 2010).

The dust grains comprise sub-micron amorphous and crystalline silicates (both the olivine, Mg<sub>2</sub>SiO<sub>4</sub>–Fe<sub>2</sub>SiO<sub>4</sub>, and pyroxene, MgSiO<sub>3</sub>–FeSiO<sub>3</sub>, solid solution series), amorphous carbon, and many other species (Gail & Hoppe, 2010). Their size distribution is established from the extinction, scattering, and polarisation properties of the cloud as a function of wavelength. At low temperatures, the more volatile molecular gases condense onto the dust grains as icy mantles. Rising temperatures in the collapsing molecular clouds lead to the sublimation of the icy mantles and, in the innermost regions of the forming protoplanetary disk, the less volatile and more refractory dust grains.

### 10.2.2 Protostars and protostellar collapse

Star formation starts with some process which initiates gravitational collapse in the molecular cloud. This process is uncertain, but may be related to highly supersonic turbulent flow (e.g. McKee & Ostriker, 2007; Folini et al., 2014; Bertelli Motta et al., 2016).

Whatever the trigger, local density enhancements due to the compression of finite volumes within the flow become gravitationally unstable. According to the *Jeans instability criterion* (Jeans, 1902), this occurs if their size  $\lambda$  exceeds the critical Jeans length

$$\lambda_J = \left( \frac{\pi c_s^2}{G\rho} \right)^{1/2}, \quad (10.1)$$

where  $c_s^2 = kT/\mu$  is the isothermal sound velocity,  $\mu$  is the mean molecular weight ( $\sim 2m_{\text{H}}$  for a gas predominantly composed of  $\text{H}_2$ ),  $T \sim 10$  K is the gas temperature, and  $\rho$  is the local density. The corresponding Jeans mass is  $M_{\text{Jeans}} \equiv (4\pi/3)(\lambda_J/2)^3\rho$ .

If  $\lambda > \lambda_J$  thermal pressure cannot resist self-gravity, and runaway collapse follows. This leads to an isothermal near free-fall contraction, during which the density increases by some 15 orders of magnitude. Contraction continues until the central region becomes opaque, compressional heating starts to exceed radiative cooling of the gas–dust mixture, and the temperature rises.

The gravitational time scale is usually expressed in terms of the *free-fall time*, the time taken for a pressure-free, spherical cloud to collapse to a point owing to its self-gravity (McKee & Ostriker, 2007, eqn 14)

$$t_{\text{ff}} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \approx 6.4 \times 10^4 \text{ yr} \left( \frac{M}{M_\odot} \right) \left( \frac{T}{10\text{K}} \right)^{-3/2}. \quad (10.2)$$

Collapse proceeds through the dissociation of  $\text{H}_2$  and the ionisation of H, leading to the formation of a protostellar embryo, which continues to grow in mass by accreting material from its local environment.

The time scales for the early stages of spherically symmetrical collapse of low-mass stars are short:  $\sim 1t_{\text{ff}}$  from initial collapse to the protostellar embryo, and  $\sim 4t_{\text{ff}}$  for the subsequent 80% of the remaining stellar mass. Accretion of the final 20% of mass occurs on a much longer time scale of about 0.5 Myr for a  $1M_\odot$  star (Wuchterl & Tscharnuter, 2003).

The resulting stars shine by thermonuclear fusion, with stable hydrogen burning occurring for masses above  $\sim 0.07 - 0.09M_\odot$  ( $\sim 75 - 95M_J$ ), depending on chemical composition, when the central temperature triggers nucleosynthesis. The most massive stars thereafter evolve rapidly, creating new elements by nucleosynthesis, and dispersing them through gaseous outflows or supernova explosions. Part of the chemically-enriched material remains in the gas phase, while part

#### Protostellar, protoplanetary, transition, and debris disks:

During the early stages of star formation, the star-forming cloud, the accretion disk feeding the stellar embryo, and the stellar embryo itself, are usually referred to as *protostellar*. In the later phases of protostar evolution, as astronomical interest shifts to planet formation within the residual gas and dust, the disk is referred to as *protoplanetary*. There is, however, no specific point at which the disk becomes unambiguously ‘protoplanetary’, and the distinction between *protostellar disks* and *protoplanetary disks* is accordingly somewhat arbitrary.

As a subset of protoplanetary disks in their late evolutionary stage, but while still containing gas (and therefore typically at ages still below 3–5 Myr), *transition disks* start to show spectroscopic or morphological evidence for inner holes and gaps which may point to developing disk–planet interactions, and even (proto-)planets in early stages of formation (§10.3.8).

Later in the process of planet formation, as planetesimals and protoplanets have formed and start a new phase of collisional attrition, the resulting circumstellar disks are referred to as *debris disks* (§10.6). This phase extends from ages of around 10 Myr to as much as several Gyr.

A characterisation of the first 40 Myr of circumstellar disk evolution, from a unified study of the infrared properties of members of young clusters and associations with ages from 2–40 Myr, is given by Meng et al. (2017).

condenses into solid dust grains, together providing material for subsequent generations of star formation.

Within this broad picture, at least two aspects of the microphysics of star formation remain uncertain: the process by which an unstable region fragments into the many sub-units necessary to create star clusters, and the process which leads to the significant fraction of binary and multiple stars (McKee & Ostriker, 2007).

Brown dwarfs, which occupy the mass range of about 13–80  $M_J$ , are broadly considered to have been formed by the same physical process, and may experience partial hydrogen burning, and deuterium and/or lithium burning according to mass (§9.1.1). Below about 12–13  $M_J$ , objects derive no luminosity from thermonuclear fusion at any stage in their evolutionary lifetime (Burrows et al., 1993; Saumon et al., 1996). The discovery of even lower mass substellar objects in young clusters, down to  $\sim 1M_J$  or below, may still be consistent with formation through the same process (§9.7).

**Initial disk collapse** The material within a gravitational unstable region of a molecular cloud inevitably carries some angular momentum, which prevents the collapsing material from falling directly onto the stellar embryo. Instead it falls, by symmetry, onto a flat rotating disk in the plane through the centre of mass and orthogonal to the total angular momentum of the cloud.

The fraction of the gas and dust falling onto the disk rather than directly onto the star depends on the angular momentum of the collapsing cloud, but may exceed 90%. For high disk/protostar mass ratios the disk is



gravitationally unstable, spiral waves develop, and rapid mass accretion onto the star continues until the mass ratio falls below the Toomre instability limit. For a thin axisymmetric collisionless disk, Toomre (1964) showed that a non-axisymmetric perturbation will be gravitationally unstable if the parameter

$$Q = \frac{c_s \Omega}{\pi G \Sigma} < 1, \quad (10.3)$$

with  $Q \approx 1$  implying marginal (in)stability. Here,  $c_s = (\gamma P/\rho)^{1/2}$  is the sound speed,  $\Omega = (GM_\star/R^3)^{1/2}$  is the Keplerian angular frequency at radius  $R$ , and  $\Sigma$  is the disk *surface density*, i.e. the projected mass per unit area at a given radial distance.

The angular momentum of the residual disk material prevents its rapid inspiraling onto the star. Any subsequent inward migration of mass requires an outward transfer of angular momentum. Such a process only occurs on the time scale of viscous disk accretion, which is much longer than the formation time of the initial stellar embryo, and it is the inefficiency of this (incompletely understood) accretion process which makes planet formation possible.

Disk evolution, proceeding from the massive accretion disks to more tenuous protoplanetary disks, is determined by viscosity, accretion onto the central star, grain coagulation, and photoevaporation.

A plausible overall evolutionary chronology is shown in Figure 10.2, where ages are reckoned from the time of initial collapse. Massive accretion disks appear typical for stars with ages  $\lesssim 1$  Myr. These evolve to lower mass protoplanetary disks, with little or no ongoing accretion, which usually fall in the age range 1–10 Myr. Disks older than  $\sim 10$  Myr are generally non-accreting debris disks, i.e. secondary disks generated by collisional process at later evolutionary stages (§10.6).

### 10.2.3 Young stellar objects

Within the newly-formed accretion disks, young stellar objects mark the sites of the earliest stages of disk and planet formation. They are generally characterised by an infrared excess due to hot dust in the disk, and possibly also an ultraviolet excess attributed to hot spots resulting from material accreting onto the stellar surface. Young stellar objects show evidence of stellar winds and outflows, including the Herbig–Haro type collimated jets (Figure 10.3), phenomena which accompany mass accretion that interacts with magnetic fields and rotation (Königl & Pudritz, 2000; Pudritz et al., 2007).

Young stellar objects are frequently assigned to one of four classes (André et al., 2000), according to their spectral index over the wavelength region  $2.5\text{--}10\ \mu\text{m}$  and beyond

$$\alpha_{\text{IR}} = \frac{d \log \lambda F_\lambda}{d \log \lambda}, \quad (10.4)$$

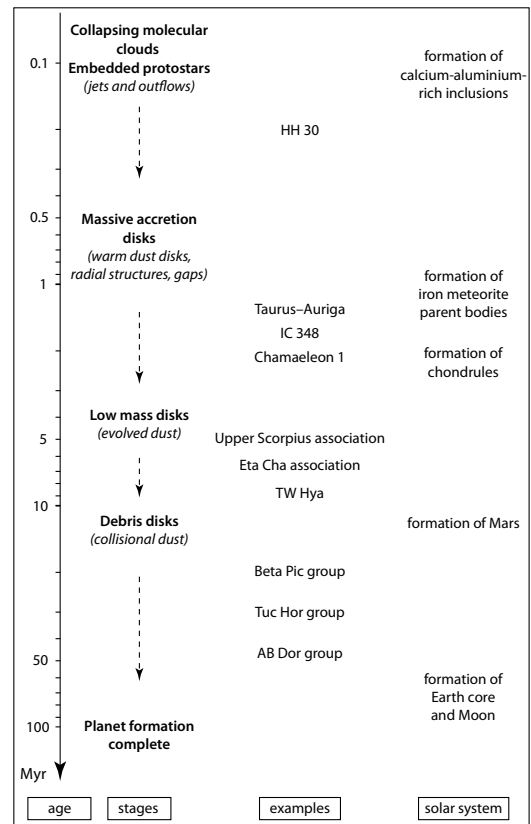


Figure 10.2: Chronology of the early stages of planet formation, from an arbitrary initial time, showing some of the main evolutionary stages, some representative astronomical examples, and some specific epochs relevant for the solar system (see also §12.1.4). The figure is an adaptation of a more detailed chronology given by Apai & Lauretta (2010, Figure 1.3).

and which also reflects their successive evolutionary stages (e.g. Adams et al., 1987; Gail & Hoppe, 2010; Wolff et al., 2011):

Class 0: sources with a very faint protostar in the optical and near infrared, and with a spectral energy distribution peaking in the far infrared or sub-mm region. These are sources in which the molecular cloud is starting to collapse, and in which the stellar embryo and its associated disk are starting to become established;

Class I: sources with a spectral energy distribution flat or rising into the mid-infrared,  $\alpha_{\text{IR}} > 0$ . These are protostars with circumstellar disks and envelopes. During this phase, stars accrete most of their final mass from the disk and the surrounding gas and disk envelope;

Class II: sources with a spectral energy distribution declining into the mid-infrared,  $-1.5 < \alpha_{\text{IR}} < 0$ . These are the pre-main sequence stars with observable accretion disks (*classical T Tauri stars*);

Class III: sources with little or no infrared excess,  $\alpha_{\text{IR}} < -1.5$ . These are pre-main sequence stars without

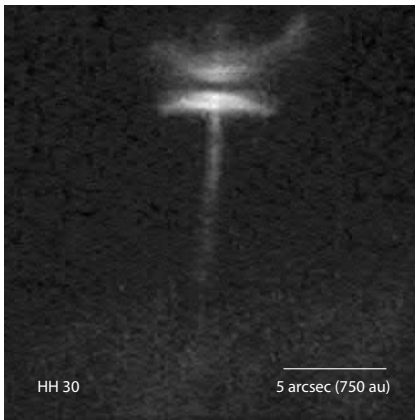


Figure 10.3: The Herbig-Haro object HH30, at a distance of  $\sim 150$  pc, observed by HST. Two thin jets flow outwards from the young stellar object in the centre. The two lenticular regions are scattered light from dust in the disk. The dark central lane is the accretion disk observed edge-on (courtesy NASA/ESA/STScI).

detectable accretion, in which the initial disk has been largely cleared (*weak-lined T Tauri stars*).

The early evolutionary stages (classes 0 and I) are optically hidden by the dust of the collapsing envelope, and are only observable in the far-infrared. The optically visible class II–III sources reach some 90% of their final mass at the transition between the classical and weak-lined T Tauri phases, which occurs for solar-mass stars some  $2 \times 10^5$  yr after the onset of collapse.

Understanding the chemical and isotopic composition and evolution of protoplanetary disks during these different phases is limited by the sensitivity and spatial resolution of the necessary (sub)mm interferometric observations. Nevertheless, radio-interferometric studies, Spitzer and Herschel observations, laboratory experiments, and meteoritic measurements are all contributing to a developing picture of the relevant physical and chemical processes (Semenov et al., 2010; Min, 2010).

### 10.3 Protoplanetary disks

Over the next few million years, most of the remaining disk mass is accreted, the residual gas is dispersed, and the star proceeds on its final evolution to the main sequence as a class III object. This final phase of protostar evolution is loosely referred to as protoplanetary, and it is within the *protoplanetary disk* that the processes of planet formation develop.

As noted at the start of this chapter, there is no specific point at which the disk becomes unambiguously protoplanetary, and the distinction between protostellar disks and protoplanetary disks is somewhat arbitrary. However it is in the protoplanetary disk that the first stages of planet formation, both for terrestrial planets, and for the gas and ice giants, take place.

The study of protostellar and protoplanetary disks is an extensive field, with a substantial body of both observational and theoretical support. Only an outline of the phases of disk evolution most relevant for planet formation are given here. Developing reviews give further details and additional references to the relevant literature (e.g. Benz, 2000; Dominik et al., 2007a; Ciesla & Dullemond, 2010; Dullemond & Monnier, 2010; Youdin, 2010; Armitage, 2011; Beuther et al., 2014; Dutrey et al., 2014; Inutsuka, 2014; Johansen et al., 2014; Birnstiel et al., 2016; Baruteau et al., 2016).

**Organisation of material** This treatment divides the planet formation processes into two parts. This section, devoted to protoplanetary disks, details the phenomena and physical processes that are important in understanding and modeling these first stages of growth, and which are most easily classified as ‘disk-like’. Amongst these are the problems of radial drift, the origin of gas turbulence, and the various mechanisms that are considered able to concentrate particles within the turbulent flow. Subsequent sections detail growth phases that are more ‘object-like’, starting with particle aggregation at the smallest sizes, and the associated growth ‘barriers’ of bouncing and fragmentation, considering sequentially the subsequent stages of terrestrial planet formation (§10.4) and giant planet formation (§10.5).

**Complexities** Protoplanetary disks are quasi-steady state structures whose appearance, lifetime, evolution, and eventual dispersal, determines the environment for planet formation. The relative importance of a range of dynamical, angular momentum transport, and radiative processes, including self-gravity, gas viscosity, turbulence, magnetorotational instability, baroclinic instabilities, and magnetic field effects, depends on the initial mass, size, rotation and magnetisation of the disk, and subsequently on its chemical composition, opacity, ionisation state, and external irradiation. The early stages of planet formation are therefore closely coupled to star formation, pre-main-sequence stellar evolution, and dust coagulation.

Molecules and dust serve as major heating and cooling agents within disks. Dust grains dominate the disk opacities, reprocess most of the stellar radiation, and shield molecules from ionising ultraviolet and X-ray photons. Disks also dynamically evolve through the building up of planetary systems, which drastically change their gas and dust density structures. A variety of infrared and (sub-)mm facilities are also providing insights into their morphology and chemistry.

The physics involved in the various stages of planet formation is correspondingly complex, may vary dramatically from system to system, and with a number of aspects still uncertain or ambiguous. Some of the current challenges are summarised by Haworth et al. (2016).

**Planetesimal growth: the big picture** The first stages of planet formation, within the protoplanetary disk, are particularly complex, although while many details remain uncertain, the broad principles appear to be in place. Once ‘planetesimals’ have formed, the subsequent stages of terrestrial planet formation are dominated by gravitational interactions and are (arguably) more straightforward to model. Indicative time scales for the overall process are illustrated in Figure 10.4.

The accumulation of dust and ice particles into planetesimals is an important first step in the planet formation process (Johansen et al., 2014). Planetesimals are the seeds of both terrestrial planets and the solid cores of gas and ice giants forming by core accretion. Leftover planetesimals (in the form of asteroids, trans-Neptunian objects, and comets) provide a record of the physical conditions in the solar nebula. Debris from planetesimal collisions around other stars signposts that the planetesimal formation process, and hence planet formation, is ubiquitous in the Galaxy. The planetesimal formation stage extends from  $\mu\text{m}$ -sized dust and ice to bodies that can undergo runaway accretion. The latter ranges in size from 1–1000 km, dependent on the planetesimal eccentricity excited by turbulent gas density fluctuations.

There are many barriers to this early growth, arising mainly from inefficient sticking, fragmentation, and radial drift. Promising growth pathways include mass transfer, where small aggregates transfer up to 50% of their mass in high-speed collisions with much larger targets; and fluffy growth, where cross sections and sticking probabilities are enhanced by a low internal density.

A wide range of particle sizes, from 1 mm–10 m, can concentrate in the turbulent gas flow which exists within the protoplanetary disk. It is believed that overdense filaments then fragment gravitationally into bound particle clumps, with most mass entering planetesimals of radii 100–500 km, depending on local disk properties.

**Overall disk morphology** At early epochs, when the disk mass is largest, *active circumstellar disks* are characterised by the conversion of gravitational energy into thermal radiation as gas flows inwards and accretes onto the star (Pringle, 1981; Frank et al., 2002). Towards the end of the accretion and gas clearing phase, *passive circumstellar disks* derive most of their luminosity from reprocessed starlight.

With certain assumptions, for example that the disk absorbs all incident stellar radiation and re-emits it as a single temperature blackbody, the shape and radial temperature profile of a passive disk can be estimated (Adams & Shu, 1986; Kenyon & Hartmann, 1987; Chiang & Goldreich, 1997; Armitage, 2007a). The vertical structure of the disk, determined by hydrostatic equilibrium, may *flare*, i.e. become thicker with increasing radius, in which case the outer disk regions will intercept a larger

**Planetesimals, embryos, and protoplanets:** The term *planetesimal* is loosely defined as a solid object arising during planet formation which is held together by self-gravity rather than by material strength, and whose orbital dynamics are not significantly affected by gas drag. This corresponds to objects of minimum sizes of order 100 m–1 km in the solar nebula. The description is retained for objects up to 100–1000 km or so in size, when dominant ‘embryos’ or ‘protoplanets’ start their accelerated growth towards potential planets (e.g. Benz, 2000). The term *embryo* is applied to objects which are growing in size at the expense of others, and which will eventually grow to form planets.

fraction of the stellar photons, leading to higher temperature regions at larger radial distances.

The spectral energy distribution of such a disk can be derived by integrating the temperature of the disk at each radius, weighted by the contributing annular area. Mid-plane temperature profiles vary from  $T \propto r^{-1/2}$  for a flared disk, to the more rapidly declining  $T \propto r^{-3/4}$  for a flat disk (Kenyon & Hartmann, 1987). The highest temperatures in a static disk are reached at its innermost edge, closest to the star.

Chiang & Goldreich (1997) showed that a passive disk comprising a hot surface dust layer that directly re-radiates half the stellar flux, combined with a cooler disk interior that absorbs and re-emits the rest as thermal radiation, reproduces most observed spectral energy distributions when allowing for a flaring geometry (see also Dullemond et al., 2007; Baillié & Charnoz, 2014).

### 10.3.1 Minimum-mass solar nebula

Attempts to infer the general structure of protoplanetary disks were made by Weidenschilling (1977b) and Hayashi (1981). They reconstructed the solar nebula by taking the mass of solid material presently in the form of planets and asteroids, distributing it across its ‘feeding zone’ to form a smooth distribution, adding the amount of H and He at each location to produce a solar composition, and arguing that the resulting structure represented the least amount of initial material needed to form the solar system. This *minimum-mass solar nebula* (MMSN) was described by a radial surface density profile,  $\Sigma(r)$ , and temperature profile,  $T(r)$  given by

$$\begin{aligned}\Sigma(r) &= 1.7 \times 10^4 r_{\text{au}}^{-3/2} \text{ kg m}^{-2}, \\ T(r) &= 280 r_{\text{au}}^{-1/2} \text{ K},\end{aligned}\tag{10.5}$$

where  $r_{\text{au}}$  is the radial distance from the Sun in au. This structure produced a disk with a mass between 0.01 – 0.07  $M_{\odot}$  out to 40 au. Although subject to uncertainties, the concept of a minimum-mass solar nebula remains a point of reference in quantifying the mass contained both within protoplanetary disks, and within more mature planetary systems (Kuchner, 2004). Such models are often termed a *minimum-mass extrasolar nebula* (MMEN). Examples are shown in Figure 10.26.

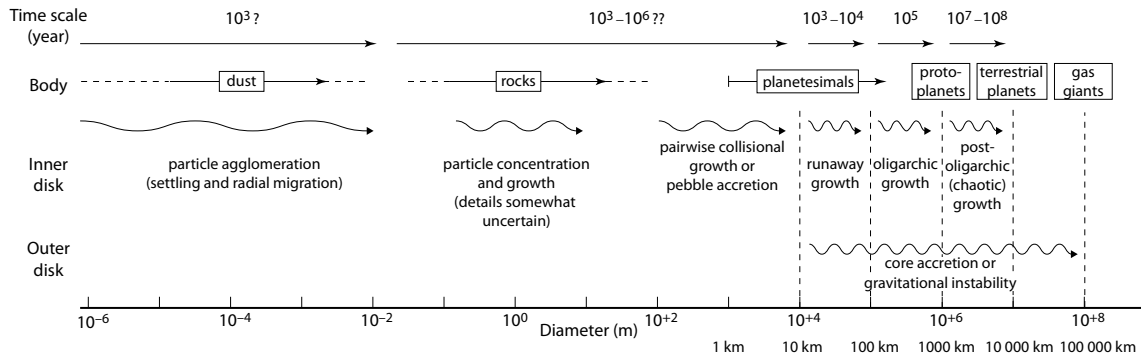


Figure 10.4: Schematic of the growth of planets, starting with sub-micron dust, and extending up to the terrestrial planets in the inner disk, and the gas giants in the outer disk. Some indicative time scales are given, although some intervals, especially around the bouncing/fragmentation barrier (of order 1 m), remain particularly uncertain.

Estimating the mass of real protoplanetary disks is not straightforward. The largely molecular hydrogen gas cannot be measured directly, so that mass estimates are based on mm observations which trace the distribution of solid bodies up to  $\sim 0.01$  m in size, and further assumptions about the size distribution and dust-to-gas ratio (Piétu et al., 2007; Andrews & Williams, 2007).

Mass estimates obtained in this way are reasonably consistent with the range given by the minimum-mass solar nebula hypothesis (Williams et al., 2005), scaling roughly linearly with the mass of the central star (Klein et al., 2003). ALMA observations of various 1–3 Myr old star-forming regions suggest a steeper than linear form,  $M_{\text{dust}} \propto M_{\star}^{1.3-1.9}$  (Pascucci et al., 2016).

For M dwarfs, estimates derived from Kepler planets indicate a total disk mass of  $0.009M_{\odot}$ , and a power-law profile with index  $\alpha = 2.2$  (Gaidos, 2017a).

**Initial chemistry** The process of planet formation starts with the gas and dust in molecular clouds, collapsing to form a thin protoplanetary disk orbiting the star. Characteristic disk masses are between  $10^{-4} - 0.1$  that of the central star, e.g. in the case of young stellar objects in Taurus–Auriga, following a log–normal distribution with a mean mass of  $5 \times 10^{-3}M_{\odot}$  and a large dispersion of about 0.5 dex (Andrews & Williams, 2005). The detailed composition of the cooling gas and dust is determined by the associated chemical equilibrium as a function of temperature and pressure, establishing which gases form, which elements or compounds condense, and in what proportions (§11.2.2).

**Dust** Dust comprises some 1% of the mass of the interstellar medium. It is characterised by condensed particles with sizes ranging from sub-micron and upwards. Interstellar dust has a diverse origin, the constituent matter having either condensed in the winds of evolved stars and in the ejecta of nova and supernova explosions, or having formed in dense interstellar clouds (Apai & Lauretta, 2010; Gail & Hoppe, 2010). The composition of protoplanetary dust can be inferred from infrared ob-

servations of protoplanetary dust around young stars (e.g. Min, 2010), and from the laboratory analysis of solar system dust.

### 10.3.2 Disk viscosity and turbulence

Inferred accretion rates for the active circumstellar disks around classical T Tauri stars are estimated at  $10^{-9} - 10^{-7}M_{\odot} \text{ yr}^{-1}$  (e.g. Gullbring et al., 1998). But it was originally a challenge to understand how or why disk material should flow inwards at these high rates. To do so, material must lose significant angular momentum.

It was inferred that some form of frictional forces act to redistribute the disk matter, allowing most of it to move inwards, while some is displaced outwards to absorb the excess angular momentum. The terms *viscosity* and *viscous heating* are frequently used in connection with this angular momentum redistribution.

Early ideas, set out to explain accretion disks in general, including those around black holes, involved shear-driven turbulence (e.g. Lüst, 1952; Shakura & Sunyaev, 1973; Lynden-Bell & Pringle, 1974; Hartmann et al., 1998). Qualitatively, shear arises because gas closer to the centre rotates more rapidly than in the outer disk regions. It then breaks down into turbulent flow which, in turn, produces the torques needed to transport angular momentum from an inner fluid element to one farther out. Over time, the disk is therefore expected to grow in radius while decreasing in mass, resulting in a decreasing accretion rate. This appears to be consistent with the statistics of accretion rate for sources of different ages (Sicilia-Aguilar et al., 2004). Alternatively, angular momentum could be lost in a magnetically-driven wind (Blandford & Payne, 1982).

Somewhat independent evidence for the existence of turbulence was suggested by Dullemond & Dominik (2004), who found that laminar settling of dust grains could not account for the observed flaring of disks, suggesting that turbulence is maintaining the distribution of particles throughout the disk height.

**Viscosity and viscous heating** Classical molecular (kinematic) viscosity is negligible in protoplanetary disks: for a gas, it is given by (e.g. Armitage, 2007a, eqn 66)

$$\nu \sim \lambda c_s, \quad (10.6)$$

where  $\lambda$  is the mean free path, and  $c_s$  is the sound speed. For a gaseous disk of surface density  $\Sigma = 10^4 \text{ kg m}^{-2}$ , and aspect ratio  $h/r = 0.05$  at  $1 \text{ au}^2$ , Armitage (2007a) gives  $\lambda \sim 0.025 \text{ m}$ ,  $\nu \sim 40 \text{ m}^2 \text{ s}^{-1}$ , and a resulting disk evolution time scale  $\tau \sim r^2/\nu \sim 10^{13} \text{ yr}$ , some  $10^6$  times slower than that observed.

The current view is that various disk instabilities (including magnetorotational and streaming) drive turbulence, which in turn increases the effective viscosity (e.g. Klahr et al., 2006).

Irrespective of the nature of the angular momentum transport, it can be parameterised by an effective viscosity,  $\nu$ , which is usually scaled to the local sound speed  $c_s$  and the pressure scale height of the disk  $h$  by a dimensionless constant  $\alpha$ , which measures the efficiency of turbulence in creating angular momentum transport (Shakura & Sunyaev, 1973)

$$\nu = \alpha c_s h, \quad (10.7)$$

where the maximum scale of turbulence is of order the disk scale height, and the maximum turbulent velocity is comparable to the sound speed. Observations of such protoplanetary ‘ $\alpha$ -disks’ suggest  $\alpha \sim 0.01$  (Hartmann et al., 1998), and time-dependent calculations of the structure and evolution of the primordial solar nebula during the viscous diffusion stage suggest a similar value (Ruden & Lin, 1986). In  $\beta$ -disks, shear instabilities provide the viscosity (Richard & Zahn, 1999).

Other suggestions for generating turbulence in protoplanetary disks include various non-linear hydrodynamic instabilities (Balbus et al., 1996; Godon & Livio, 1999a; Ioannou & Kakouris, 2001; Afshordi et al., 2005; Balbus, 2006; Balbus & Hawley, 2006; Ji et al., 2006; Shen et al., 2006); and convection (Ryu & Goodman, 1992; Stone & Balbus, 1996).

### 10.3.3 Radial drift

As particles start to aggregate and grow within the disk, through the processes described in more detail in Section 10.4.1, inward radial drift occurs rapidly, and sets a strict boundary condition on the speed with which the early growth phases must occur. This can be understood as follows (e.g. Johansen et al., 2014, Section 3.2).

Protoplanetary disks are slightly pressure-supported in the radial direction, due to gradients in both mid-plane density and temperature, leading to a sub-Keplerian motion of the gas (Nakagawa et al., 1986), of  $\Delta v \sim 50 \text{ m s}^{-1}$  with respect to the Keplerian speed,  $v_K$ , for a wide range of disk models (Bell et al., 1997).

Dust grains and smaller bodies are well-coupled to the circulating gas, and orbit the protostar in the same direction and in the same plane. They are subject to aerodynamic drag by the gas, with a force (Weidenschilling 1977a, eqn 7; Armitage 2007a, eqn 106)

$$f_d = -\frac{1}{2} C_d (\pi a^2) (\rho v^2), \quad (10.8)$$

where  $a$  is the particle radius (assumed spherical), and the gas of density  $\rho$  moves with velocity  $v$ . The drag coefficient,  $C_d$ , depends on the particle size compared to the mean free path  $\lambda$  of the gas molecules (Weidenschilling, 1977a). The resulting force is termed *Stokes drag* for  $a > 9\lambda/4$ , i.e. above  $\sim 0.01 \text{ m}$  in size (Stokes, 1851), and *Epstein drag* for smaller particles (Epstein, 1924).

The drag on the embedded particles leads to particle drift in both the radial and azimuthal directions (Weidenschilling 1977a; Johansen et al. 2014, eqn 9–10)

$$v_r = -\frac{2\Delta v}{\text{Stk} + \text{Stk}^{-1}} \quad (10.9)$$

$$v_\phi = v_K - \frac{\Delta v}{1 + \text{Stk}^2}, \quad (10.10)$$

where  $\text{Stk}$  is the (dimensionless) *Stokes number*

$$\text{Stk} = \Omega \tau_f, \quad (10.11)$$

where  $\Omega$  is the Keplerian frequency at the given orbital distance and  $\tau_f$  is the friction time, again dependent on  $\lambda$  and the speed of the particle relative to the gas (Weidenschilling, 1977a). The Stokes number characterises the behaviour of particles in, and coupling to, a fluid flow (such that particles with different sizes, densities, or shapes, but the same Stokes number, are aerodynamically identical), and controls not only the radial and azimuthal particle drift, but also turbulent collision speeds, particle sedimentation, concentration in pressure bumps and vortices, and concentration by streaming instabilities (topics which are detailed below).

Larger rocks are less strongly coupled to the gas, and move with the slightly larger Keplerian disk velocity. The result is a loss of orbital angular momentum, and again a net inward particle drift (Takeuchi & Lin, 2002; Youdin & Chiang, 2004; Takeuchi et al., 2005a; Armitage, 2007a; Laibe et al., 2012).

The peak inspiraling rate, at  $\sim 1 \text{ au}$ , occurs for particle sizes  $\sim 0.01 - 10 \text{ m}$ , leading to rapid radial drift time scales of order  $100 \text{ yr}$  (e.g. Adachi et al., 1976; Weidenschilling, 1977a). Such a rapid radial drift implies that particle growth up to  $\sim 10 \text{ m}$  in size must be rapid, of order  $100-1000$  orbits (Brauer et al., 2007a,b, 2008a).

**Modified radial drift** Various other effects modify, and moderate, the simple picture of rapid inward radial drift: *Fluffy particles*: ‘fluffy’ particles, with low bulk density, arise if impact compactification is negligible (Okuzumi et al., 2009; Zsom et al., 2010, 2011a; Okuzumi et al., 2012). These can reach unity Stokes number, where the radial drift is highest, in the Stokes drag regime. At this point, the Stokes number (which determines radial drift) increases as the square of the particle size, and results in more rapid growth to Stokes numbers for which radial drift is unimportant (Okuzumi et al., 2012).

*Sublimation*: the inwardly drifting particles do not fall into the star, but rather sublimate at *evaporation fronts*,

<sup>2</sup>Such a surface density, typical of that considered for protoplanetary disks, may be compared with that of the local mean Galactic disk surface density, e.g. within  $1100 \text{ pc}$ , of  $\Sigma (1100 \text{ pc}) \sim 52.8 M_\odot \text{ pc}^{-2}$  (Holmberg & Flynn, 2004), or  $\sim 0.1 \text{ kg m}^{-2}$ .

or snow lines, leading to the pile up of material around these fronts (Cuzzi & Zahnle, 2004; Wang, 2015; Estrada et al., 2016). This leads to particle growth by condensation of H<sub>2</sub>O vapour onto existing ice particles (Kuroiwa & Sirono, 2011; Ros & Johansen, 2013), considered in the case of Jupiter by Stevenson & Lunine (1988).

**Streaming instabilities:** the radial drift flow of particles is linearly unstable to *streaming instabilities*, driven by differences in the motions of the gas and solid particles in the disk (Youdin & Goodman, 2005). This can lead to further particle concentration in dense filaments, aiding planetesimal formation by more rapid growth (Goodman & Pindor, 2000; Haghighipour & Boss, 2003; Rice et al., 2004; Durisen et al., 2005; Youdin & Goodman, 2005; Youdin & Johansen, 2007; Johansen & Youdin, 2007; Johansen et al., 2009b; Bai & Stone, 2010a,b; Johansen & Klahr, 2011; Kowalik et al., 2013; Drazkowska & Dullemond, 2014; Yang & Johansen, 2014; Simon et al., 2016; Carrera et al., 2017; Simon et al., 2017; Yang et al., 2017a). Streaming instability benefits strongly from increased disk metallicities (Johansen et al., 2009b; Bai & Stone, 2010a), an effect perhaps contributing to the higher occurrence rate of exoplanets around higher metallicity stars. Various simulations are illustrated at [jila.colorado.edu/~jasi1566](http://jila.colorado.edu/~jasi1566).

**Erosion:** of pre-planetesimals by tiny dust grains carried with the sub-Keplerian wind (Schr apler & Blum, 2011; Seizinger et al., 2013).

**Photophoresis:** in which a temperature gradient along a gas-embedded particle leads to the particle's motion away from the light source, slowing down or reversing its inward motion (e.g. Rohatschek, 1995; Krauss & Wurm, 2005; Herrmann & Krivov, 2007; von Borstel & Blum, 2012; Duermann et al., 2013; de Beule et al., 2013; Loesche et al., 2013; Teiser & Dodson-Robinson, 2013; Wurm et al., 2013; McNally & McClure, 2017). It is possibly accompanied by radial and vertical sorting according to size and density (Cuellar et al., 2016).

**Radial drift combined with fragmentation** Particle growth, and the associated collisional effects of fragmentation and bouncing, are described in Section 10.4.2. Anticipating these details, it is useful to emphasise that while barriers to particle growth beyond a few 0.1 m include grain fragmentation as well as radial drift, it is their combined effects that determine the associated growth barriers. These combined effects vary with radial distance and turbulence parameter.

Where the limit is set by fragmentation due to relative turbulent motion, analytical models suggest that a significant fraction of the dust mass is concentrated in the largest sizes, slightly below the limiting Stokes number (Birnstiel et al. 2011; Birnstiel et al. 2012b, eqn 8)

$$a_{\text{frag}} \sim \frac{2}{3\pi} \frac{\Sigma_{\text{gas}}}{\rho_s \alpha} \frac{u_f^2}{c_s^2}, \quad (10.12)$$

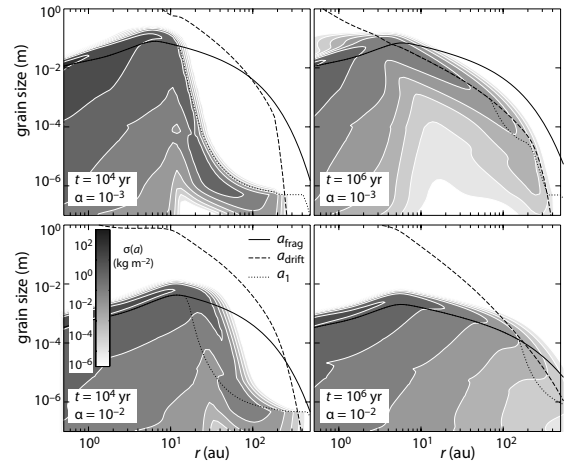


Figure 10.5: Effects of radial drift combined with fragmentation, showing dust surface density versus radius and grain size at 10<sup>4</sup> yr (left panels) and 10<sup>6</sup> yr (right panels), and for turbulence parameter  $\alpha = 10^{-3}$  (upper pair), and  $\alpha = 10^{-2}$  (lower pair). Lines show typical sizes for a fragmentation-limited size distribution (solid; Equation 10.12) and for a drift-limited size distribution (dashed; Equation 10.13). Dotted lines indicate the (time-dependent) largest grain size  $a_1(t)$ . From Birnstiel et al. (2012b, Figure 1–2), reproduced with permission © ESO.

where  $\Sigma_{\text{gas}}$  is the gas surface density (Brauer et al., 2008a),  $\rho_s$  is the internal density of the dust aggregate (taken as 1.6 Mg m<sup>-3</sup>),  $\alpha$  is the turbulence parameter (Equation 10.7),  $u_f$  is the fragmentation threshold velocity, and  $c_s$  is the isothermal sound speed.

**Fragmentation velocities** Laboratory experiments suggest  $u_f \sim 1 \text{ m s}^{-1}$  for the onset of fragmentation for silicate grains (e.g. Blum & Wurm, 2008). The fragmentation velocity decreases with grain size (Beitz et al., 2011), an effect partly attributable to the growing importance of inhomogeneities in larger grains (Geretshausen et al., 2011b). Icy particles may fragment only at higher velocities due to order of magnitude higher surface energies (Wada et al., 2008; Gundlach et al., 2011), while for 10  $\mu\text{m}$ -size icy aggregates the fragmentation velocity could be as high as 50 m s<sup>-1</sup> (Wada et al., 2009).

If continuously replenished by growth, the maximum particle size reached before radial drift removes them is approximated by (Birnstiel et al., 2012b, eqn 18)

$$a_{\text{drift}} \sim \frac{2}{\pi} \frac{\Sigma_{\text{dust}}}{\rho_s} \frac{V_k^2}{c_s^2} \gamma^{-1}, \quad (10.13)$$

where  $\Sigma_{\text{dust}}$  is the dust surface density,  $V_k$  is the Keplerian velocity, and  $\gamma = |\text{d} \ln P / \text{d} \ln r|$  is the absolute value of the power-law index of the gas pressure profile.

Figure 10.5 shows results from simulations of a 0.1  $M_{\odot}$  disk around a solar mass star, in which the contours denote  $\sigma(a, r)$ , the dust surface density distribution per logarithmic size bin.

### 10.3.4 Magnetorotational instability

In addition to the hydrodynamical forces of pressure and gravity, a magnetised fluid is subject to Lorentz forces (the vector product of the current density and magnetic field). If the fluid is differentially rotating, this force can be highly disruptive, even if the magnetic field is weak. In particular, numerical simulations show that, if the angular velocity decreases with radial distance, the fluid flow is highly unstable: the rotating disk becomes turbulent, with perturbations growing exponentially.

First described in a non-astrophysical context by Velikhov (1959), generalised to Couette flow by Chandrasekhar (1960b), and applied to Earth's geodynamo by Acheson & Hide (1973), the theory was subsequently developed to explain turbulent flow in accretion disks (Hawley & Balbus, 1991; Balbus & Hawley, 1991, 1998).

The resulting *magnetorotational instability*, or MRI, leads to self-sustaining turbulence, an outward transfer of angular momentum, an inward mass flow with the necessary transport efficiency, and to conditions favourable for particle aggregation. MRI is believed to be involved in a wide range of accretion phenomena, including star formation, active galactic nuclei, gamma-ray bursts, and the production of X-rays in neutron star and black hole systems.

Within protoplanetary disks, turbulence driven by magnetorotational instability is now considered to have a significant influence on the early stages of planet formation (Johansen, 2009). It may dominate in certain regions of the disk, with other mechanisms driving turbulence in others. As well as providing a source of viscosity, it is also considered to generate regions in which particle concentration mechanisms can operate.

**Layered accretion and dead zones** For the MRI effect to operate in protoplanetary disks, sources of ionisation are required to enhance conductivity, to provide a coupling between the gas and magnetic field, to stimulate turbulence, and to fuel accretion (Blaes & Balbus, 1994; Gammie, 1996; Desch, 2004; Salmeron & Wardle, 2005). Direct observational evidence for ionisation also comes from estimates of H depletion (e.g. Kral & Latter, 2016).

Various ionising sources have been identified in protoplanetary disks, including collisional excitation of alkali metals at the higher temperatures and densities of the innermost parts of the disk (Umebayashi, 1983), with X-rays, cosmic rays and radionuclide decay providing ionisation sources throughout the lower column densities of the disk's outer parts, or in the surface layers elsewhere (e.g. Umebayashi & Nakano, 1981; Bai & Goodman, 2009; Umebayashi et al., 2013; Fujii et al., 2014a; Rodgers-Lee et al., 2017).

The combination (Figure 10.6) results in a *layered disk*, comprising a non-turbulent mid-plane layer, or *dead zone*, within the outer strongly turbulent structure which fuels the accretion (Gammie, 1996; Gammie &

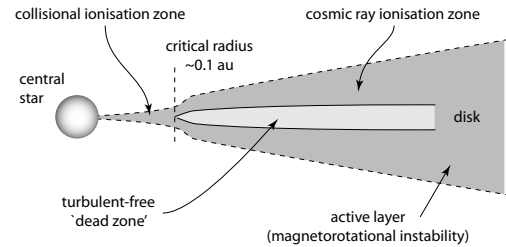


Figure 10.6: Schematic of a layered accretion disk. Inside 0.1 au, where  $T \sim 10^3$  K, collisional ionisation ensures magnetorotational instability, and enables accretion. At large radii, cosmic rays penetrate the entire disk. At intermediate radii, they ionise a layer of thickness  $\sim 10^3$  kg m $^{-2}$  on either side. Between the active layers is a 'dead zone' where turbulence and accretion are inhibited. Adapted from Gammie (1996, Figure 1).

Menou, 1998). Such a geometry provides a quiescent environment interior to the turbulent zone in which dust settling, planetesimal growth, the structured formation of terrestrial mass planets and ice giants, and the migration of low-mass planets, might all operate. The model of Gammie (1996), for example, predicts a stellar accretion rate of  $10^{-8} M_{\odot} \text{ yr}^{-1}$  independent of the rate of material infall onto the disk, with non-accreted matter accumulating in the inner few au at  $10^{-7} M_{\odot} \text{ yr}^{-1}$ . Matsumura & Pudritz (2005, 2006) found that the dead zone typically extends out to 12–15 au, acts to slow down migration due to its lower viscosity, and encourages growth of eccentricities through planet–disk interactions.

**Detailed simulations** Subsequent simulations have confirmed the presence and relevance of dead zones. They have also demonstrated that the transition region between the magnetorotationally active and dead zones are prone to the excitation of vortices via Rossby wave instability, as well as gravomagneto instabilities and associated outbursts (e.g. Armitage et al., 2001; Matsumura & Pudritz, 2003, 2005, 2006; Varnière & Tagger, 2006; Matsumura et al., 2007; Oishi et al., 2007; Turner et al., 2007; Hasegawa & Pudritz, 2010; Pierens & Nelson, 2010; Okuzumi & Hirose, 2011; Gressel et al., 2011; Charnoz & Tailifet, 2012; Gressel et al., 2012; Okuzumi & Hirose, 2012; Martin et al., 2012a; Gressel et al., 2012; Lyra & Mac Low, 2012; Martin et al., 2012b; Okuzumi & Hirose, 2012; Drazkowska et al., 2013; Martin & Lubow, 2013; Ormel & Okuzumi, 2013; Fujii et al., 2014a; Faure et al., 2015; Faure & Nelson, 2016; Kral & Latter, 2016; Pinilla et al., 2016; Gole et al., 2016).

**FU Ori-type outbursts** Dead-zone models have also been used to explain FU Ori-type outbursts. This class of highly-variable pre-main-sequence star displays extreme changes in magnitude (up to 6 mag in the case of V1057 Cyg) and spectral type. Flares have been associated with abrupt mass transfer from the accretion disk onto the star as a result of magnetic field line reconnection (Reipurth, 1990; Martin et al., 2012b).

**Regular satellites** Dead zones may also provide a favourable environment for the formation of the 'regular' planetary satellites of the solar system (Lubow & Martin, 2013, see also §12.5.10).

### 10.3.5 Trapping and particle concentration

In anticipation of discussions of growth at the lower end of particle sizes, where bouncing, fragmentation, and radial drift all represent barriers to growth (§10.4.2), current models of the early growth phases build on the idea that, even with turbulence, densities high enough for gravitational collapse can be reached within specific restricted regions of the disk (Johansen et al., 2014). Such ideas formed the basis of the Goldreich–Ward mechanism, an early suggested route for circumventing the issues confronted by growth beyond a metre or so in size, but one eventually rejected on the grounds of excessive turbulent instabilities (box, page 460).

High particle concentrations can occur through various processes, still being identified, including turbulent concentration, the gravitational collapse of overdense filaments (Figure 10.7), or (self-induced) *dust traps* (Gonzalez et al., 2017; Owen & Kollmeier, 2017).

Within turbulent regions, the size of an optimally trapped particle depends on the length-scale and turnover time scale of the turbulence. Particle trapping regimes extend from the smallest scales, viz. *eddies*, unaffected by disk rotation, (Squires & Eaton, 1991; Fessler et al., 1994; Cuzzi et al., 2001, 2008; Pan et al., 2011), through to the largest scales determined by the balance between the pressure gradient and Coriolis accelerations (termed *geostrophic balance*). In this latter category are *pressure bumps* and *vortices*, both providing possible routes for crossing the bouncing and fragmentation barriers.

The main ways of concentrating particles under these conditions, viz. turbulent eddies, zonal flows associated with large-scale pressure bumps and vortices, and streaming instabilities, are illustrated in Figure 10.8.

**Pressure bumps** Various sources of long-lived *pressure bumps*, leading to grain trapping and possibly to rapid grain growth, have been suggested.

Simulations of MRI-driven turbulence show that large-scale, long-lived pressure bumps form spontaneously and ubiquitously in the turbulent flow, with amplitudes of 1–2% of the mean pressure and life times of order 10 orbits (e.g. Fromang & Nelson, 2005; Johansen et al., 2006b; Lyra et al., 2008b; Johansen et al., 2009a; Simon et al., 2012b; Taki et al., 2016). They lead to concentrations of migrating particles into radial bands, surrounded by sub-Keplerian/super-Keplerian *zonal flows*. In this picture of *gravoturbulent formation* of planetesimals, overdensities, of some factor 100, may contract under collective self-gravity, and condense into gravitationally-bound clusters of rocks and boulders, with masses comparable to that of the dwarf planet Ceres (Figure 10.9).

Pressure bumps also arise from jumps in the turbulent viscosity, or as a result of tidal forces of an embedded planet (Lyra et al., 2008a, 2009; Dzyurkevich et al.,

**Goldreich–Ward mechanism:** Addressing the problematic middle stage in the formation of terrestrial planets and gas giant cores, viz. growth from cm to km-sized bodies, Safronov (1972) and Goldreich & Ward (1973) independently suggested an alternative formation route.

In this conceptually simple picture, small particles settle to the mid-plane (accompanied by inward radial drift) where the enhanced dust-to-gas ratio leads to gravitational instability. Clumps of some characteristic size would contract until centrifugal force becomes strong enough to balance self-gravity. Goldreich & Ward (1973) suggested that bodies  $\leq 500$  m in size could form in this way. In principle, it has the merit of a short formation time scale, bypassing the size scales that are most susceptible to radial drift. Later studies suggest that turbulence inhibits the process.

Gravitational instability of a thin axisymmetric particle layer occurs when the Toomre parameter  $Q_T \equiv c_p \Omega_0 / \pi G \Sigma_p < 1$ , where  $c_p$  is the dispersion velocity. Ward (1976, 2000) included effects of gas drag, and found that even when  $Q_T > 1$ , sufficiently long waves were unstable. Later studies suggest that gas drag does not provide robust conditions for such instabilities (Shariff & Cuzzi, 2011).

In practice, instability for standard gas to dust ratios, of order 100, requires a very thin disk layer with velocity dispersion  $\leq 0.1 \text{ m s}^{-1}$ . However, the turbulent effects of Kelvin–Helmholtz instabilities, magnetorotational instabilities, and instabilities generated by the dust disk itself (Weidenschilling, 1980, 1984), prevents the dust layer in any plausible disk from ever being this thin, such that the critical particle density required for the mid-plane gravitational instability is never realised (e.g. Cuzzi et al., 1993; Garaud & Lin, 2004; Armitage, 2007a; Shariff & Cuzzi, 2011; Takeuchi & Ida, 2012; Shi & Chiang, 2013).

Suppression of turbulence in the particle–gas layer by the vertical density gradient has also been considered and largely excluded (Sekiya, 1998; Youdin & Shu, 2002; Youdin & Chiang, 2004; Garaud & Lin, 2004; Cuzzi & Weidenschilling, 2006). Other growth scenarios in dense mid-plane layers, not relying on gravitational instabilities, have also been considered (Weidenschilling, 2000; Cuzzi et al., 2001; Johansen et al., 2006b).

2010; Gonzalez et al., 2015), and possibly due to discontinuities in particle density at the H<sub>2</sub>O snow line (Kretke & Lin, 2007; Brauer et al., 2008b; Drazkowska et al., 2013). Mean motion resonances can yield extended particle capture times (Pástor, 2016).

In these models, grains can be transported both vertically and radially by turbulent diffusion, and possibly through large-scale meridional circulation, counteracting sedimentation to the mid-plane. These processes can therefore transport crystalline material from the hot inner disk to the outer parts, as observed in some cold outer disk regions (e.g. Brandenburg et al., 1995; Stone et al., 1996; Sano et al., 2000; Gail, 2002; van Boekel et al., 2004; Flaig et al., 2010; Fromang et al., 2011; Heinzeller et al., 2011; Boss, 2013a).

**Magnetic field** The magnetic field orientation may have a strong influence on the formation of close-in planets. Observed accretion rates may only be attain-



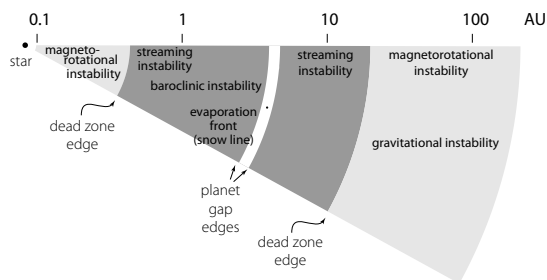


Figure 10.7: Particle concentration regions in a wedge of a protoplanetary disk, seen from above (Johansen et al., 2014, Figure 7). Regions where magnetorotational instability is expected are in light grey, while the ‘dead zone’ in a nominal disk is dark grey. The various particle trapping mechanisms are described in the text. From *Protostars and Planets VI* edited by Henrik Beuther, Ralf S. Klessen, Cornelis P. Dullemond, and Thomas Henning. ©2014 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press.

able with the inclusion of some non-negligible vertical component (Bai & Stone, 2013; Simon et al., 2013a,b). More specifically, for aligned field and angular momentum vector, values of the turbulent efficiency can reach  $\alpha \sim 0.01$  in the inner disk, but only  $\alpha \sim 10^{-4} - 10^{-3}$  if anti-aligned (Bai, 2015; Simon et al., 2015b). Simon (2016) argued that an aligned field produces higher concentrations of solids at small radii. For *in situ* formation, this may be consistent with the fact that only half of Sun-like stars harbour exoplanets packed within  $\sim 0.3$  au.

**Detailed simulations** Details of radial drift, angular momentum transport, particle concentration, accretion rates, and circulation of solids depend on factors such as the surface density, temperature profile, dust-to-gas ratio, gas–particle mutual drag, stellar irradiation, ionisation state and magnetic pressure of the protoplanetary disk, magnetic field structure and magnetic trapping, the coupling between ionised gas and dust, the effects of Ohmic dissipation and Hall diffusion, spiral shocks, MRI-driven disk winds, protostellar outflows, thermomagnetic transport, electron heating, turbulent diffusion, and the existence of dead zones and zonal flows (e.g. Whipple, 1972; Haghhighipour & Boss, 2003; Fromang & Nelson, 2005; Carballido et al., 2006; Johansen et al., 2007; Kretke & Lin, 2010; Nelson & Gressel, 2010; Suzuki et al., 2010; Bai, 2011; Podolak et al., 2011; Flock et al., 2012; Fouchet et al., 2012; Muranushi et al., 2012; Shtemler et al., 2012; Yang et al., 2012; Wardle & Salmeron, 2012; Dittrich et al., 2013; Mamatsashvili et al., 2013; Fujii et al., 2014b; Guilet & Ogilvie, 2014; Hansen, 2014; Bai et al., 2016; Bai, 2016; Clarke & Alexander, 2016; Hennebelle et al., 2016; Hubbard, 2016; Lambrechts et al., 2016; Lou & Xing, 2016; Miyake et al., 2016; Mori & Okuzumi, 2016; Rieke et al., 2016; Rodgers-Lee et al., 2016; Shadmehri, 2016; Yang & Johansen, 2016).

**Vortices** Early hydrodynamical simulations showed that an injected vorticity field can evolve into long-lived *vortices*. These can survive for hundreds of orbits in the case of anticyclonic (counter-rotating) vortices, with a radial extent comparable to the local scale height, and in the process providing a mechanism for angular momentum transport even in low-ionisation disks (e.g. Adams

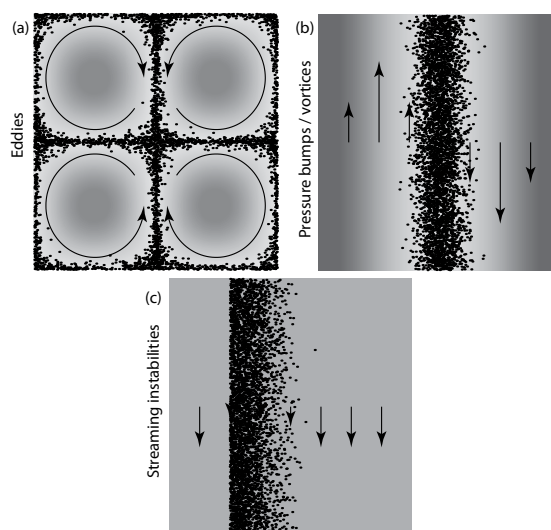


Figure 10.8: Particle concentration in protoplanetary disks (Johansen et al., 2014, Figure 6): (a) turbulent eddies near the smallest turbulence scales,  $\eta$ , expel tiny particles to high-pressure regions between the eddies (here,  $l \sim \eta \sim 1$  km,  $\text{Stk} = 10^{-5} - 10^{-4}$ ); (b) zonal flows associated with large-scale pressure bumps and vortices, of sizes from one scale height up to the global scale of the disk, trap particles with Stokes number 0.1–10 (here,  $l \sim 1 - 10H$ ,  $\text{Stk} = 0.1 - 10$ ); (c) streaming instabilities on intermediate scales trap particles of Stokes number 0.01–1 by accelerating the gas to near-Keplerian speed, which slows the radial drift in the concentration region ( $l \sim 0.1H$ ,  $\text{Stk} = 0.01 - 1$ ). From *Protostars and Planets VI* edited by Henrik Beuther, Ralf S. Klessen, Cornelis P. Dullemond, and Thomas Henning. ©2014 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press.

& Watkins, 1995; Barge & Sommeria, 1995; Tanga et al., 1996; Godon & Livio, 1999b). These early simulations also demonstrated that, rather than fragmenting into smaller vortices, small vortices tend to merge to form and sustain a large vortex.

Later work has shown that hydrodynamic flows at the dead zone boundaries of layered disks, as well as around forming objects, can provide a vorticity source. Resulting vortices can sequester particles, with typical radii 1–100 mm, that are partially decoupled from the gas. They therefore act as sites of enhanced particle growth, both inside the vortices, as well as in post-vortex rings (e.g. Chavanis, 2000; Barranco & Marcus, 2005; Johnson & Gammie, 2005; Klahr & Bodenheimer, 2006; Heng & Kenyon, 2010; Paardekooper et al., 2010b; Lin & Papaloizou, 2011b; Meheut et al., 2012a,b; Lorén-Aguilar & Bate, 2016; Surville et al., 2016; Sierra et al., 2017).

High-pressure (viz. anticyclonic) vortices may arise through *baroclinic instability*, a hydrodynamic instability that arises in rotating fluids when surfaces of constant density are inclined with respect to the surfaces of constant pressure. The vertical vorticity per unit surface density (the *vortensity*, or *potential vorticity*) is not

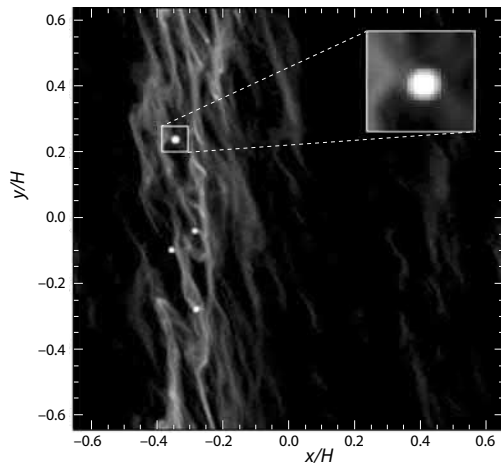


Figure 10.9: Simulations showing enhanced column densities resulting from magnetorotational instability combined with self-gravity (coordinates are with respect to the centre of the simulated region;  $H$  is the pressure scale height of the gas disk). After seven orbits, four gravitationally-bound clusters of rocks and boulders have condensed out of the flow. The largest (inset) has a mass comparable to the dwarf planet Ceres. From Johansen (2009, Figure 5), reproduced by permission of the IAU.

conserved, and pressure waves (Rossby waves) and vortices can be generated (Tritton & Davies, 1985; Barge & Sommeria, 1995; Klahr & Bodenheimer, 2003; Lesur & Papaloizou, 2010; Lin & Papaloizou, 2011a; Lyra & Klahr, 2011; Sándor et al., 2011; Raettig et al., 2013; van der Marel et al., 2013). Baroclinic instabilities are responsible for turbulent patterns including Jupiter’s Great Red Spot, and the cyclones and anticyclones on Earth.

**Jupiter’s Great Red Spot** The Great Red Spot in Jupiter’s atmosphere, which has survived for  $\gtrsim 200 - 300$  yr, is an anticyclonic vortex sustained by the merging of smaller vortices, and partially fed by strong atmospheric winds (Ingersoll, 1990; Marcus, 1993; Marcus & Lee, 1994). A specific merger in 2000, of ovals ‘FA’ itself more than 60 yr old and ‘BE’, itself the product of two 60-yr-old ovals (BC and DE) that merged in 1998, is detailed by Sanchez-Lavega et al. (2001). Other cyclones, mergers, rings, evolving colours, and inferred vertical structures and dynamics provide further cross-disciplinary insights, with further advances expected from the ongoing Juno mission (§12.2.2).

**Algorithmic implementation** Available code for related hydrodynamical simulations include AREPO, for hydrodynamics on a moving mesh (Springel, 2010); FARGO, Fast Advection in Rotating Gaseous Objects (Masset, 2000; Kley et al., 2012), and its GPU version FARGO3D (Benítez-Llambay & Masset, 2016; Benítez-Llambay et al., 2016); HERACLES, solving equations of (magneto-)hydrodynamics, radiative transfer and gravity (Audit et al., 2011; Tremblin et al., 2012); NIRVANA, including a tensor viscosity, irradiation, and radiation transport (Ziegler & Yorke, 1997; Kley et al., 2001; Bitsch & Kley, 2011a; Bitsch et al., 2013c); PENCIL (Gibbons et al., 2014; Richert et al., 2015); PIERNIK, for multi-fluid magnetohydrodynamics (Hanasz et al., 2010; Kowalik et al., 2013); PLUTO, for hypersonic flows (Mignone et al., 2007; Ormel et al., 2015); and RoSSBi (Surville et al., 2016).

### 10.3.6 Disk dispersal and photoevaporation

The lifetime of protoplanetary disks determines the time available for planet formation. As the dust and gas is successively lost, no material remains to form planetesimals, terrestrial planets, or gas giants (Ercolano, 2014).

Ages of dust disks can be estimated from the excess thermal emission emerging from small, warm dust grains. The declining fraction of stars with dust disks suggests a disk half-life of 3–5 Myr (Haisch et al., 2001; Silverstone et al., 2006; Hernández et al., 2007b; Currie et al., 2009; Bell et al., 2013; Najita & Kenyon, 2014; Pfalzner et al., 2014), at least for the fine dust, and probably progressing radially outwards. Comparable disk lifetimes of 2–4 Myr are found from some of the latest numerical simulations (Kimura et al., 2016).

**Detailed models** As the accretion rate falls, extreme ultraviolet/X-ray radiation ( $h\nu > 13.6$  eV) from the central star, or possibly from an external source (Adams et al., 2004, 2006; Chambers, 2009; Mitchell & Stewart, 2010; Facchini et al., 2016; Champion et al., 2017), irradiates gas remaining in the outer disk, and removes it from the system by Poynting–Robertson drag and photoevaporation. Gas in the surface layer is heated to  $T \sim 10^4$  K, ionised, and flows away from the star as a thermal gravitationally unbound wind (Bally & Scoville, 1982; Shu et al., 1993; Hollenbach et al., 1994; Johnstone et al., 1998; Clarke et al., 2001; Font et al., 2004; Alexander et al., 2006a,b; Richling et al., 2006; Matsuyama et al., 2009; Bae et al., 2013; Owen et al., 2013; Rosotti et al., 2013; Alexander et al., 2014; Gorti et al., 2015; Hutchison & Laibe, 2016). Dust entrainment may occur in the process (Hutchison et al., 2016b,a). Photoevaporation may also drive photoevaporative loss from the disk surface, leading to a dust-depleted outflow, and an enhanced dust-to-gas ratio in its interior (Throop & Bally, 2005; Matsuyama et al., 2009).

During disk clearing, migration may be slowed or accelerated in the region where photoevaporation opens a gap, resulting in ‘deserts’ where few giant planets are found and ‘pile-ups’ at smaller and larger radii (Terquem, 2017). Their locations and sizes are functions of the efficiency of planetary accretion, and the process has been suggested as contributing to the pile-up of Jupiter-mass planets at  $\sim 1$  au (Alexander & Pascucci, 2012; Ercolano & Rosotti, 2015; Xiao et al., 2016).

The time scale for the final stages of disk clearing by photoevaporation, corresponding to the transition between optically thick to optically thin disks in the thermal infrared, is very short. Estimates of  $\sim 10^5$  yr are inferred: (a) observationally from the population of transition objects intermediate between classical and weak-line T Tauri stars (Simon & Prato, 1995; Wolk & Walter, 1996; Ercolano & Koepferl, 2014); (b) from numerical simulations (Clarke et al., 2001; Alexander et al., 2005, 2006a,b; Martin & Livio, 2013a); and (c) from models of the protosolar nebula (Pascucci & Tachibana, 2010).

**Examples** Examples of ongoing large-scale disk clearing is seen in the HST observations of the core of the Trapezium cluster in Orion (O’Dell et al., 1993; Johnstone et al., 1998). Disks in which photoevaporation has been suggested to be ongoing include TW Hya (Ercolano et al., 2017), and the externally irradiated weakly-bound material in IM Lup (Haworth et al., 2017).

**Dependence on metallicity** Observations suggest that disk lifetimes are shorter at lower metallicities, likely due to greater susceptibility to photoevaporation (Yasui et al., 2009; Ercolano

**Circumplanetary disks:** Many of the physical effects relevant in protoplanetary (circumstellar) disks are also relevant to *circumplanetary* disks, including those forming as a result of gravitational instability. Circumplanetary disks play a role in regulating growth of the host planet (from gas and dust up to planetesimals), in the formation and extent of satellite systems, and serve as candidates for observations with instruments such as ALMA (e.g. Martin & Lubow, 2011; Mitchell & Stewart, 2011; Lubow & Martin, 2012; Rivier et al., 2012; Tanigawa et al., 2012; Bu et al., 2013; Fujita et al., 2013; Lubow & Martin, 2013; Ohtsuki et al., 2013; Shabram & Boley, 2013; Fujii et al., 2014b; Isella et al., 2014; Keith & Wardle, 2014; Tanigawa et al., 2014; Perez et al., 2015; Suetsugu et al., 2016; Suetsugu & Ohtsuki, 2016; Szulágyi et al., 2016; Zhu et al., 2016b).

& Clarke, 2010). Johnson & Li (2012) estimated the minimum metallicity for planet formation as a function of radial distance,  $r$ , by comparing the time scale for dust grain growth to that for disk photoevaporation. For a wide range of disk models and dust grain properties, they found  $[\text{Fe}/\text{H}]_{\text{crit}} \sim -1.5 + \log(r/1 \text{ au})$ .

Observationally, while it is well established that stars with high metallicity are more likely to host *giant* planets (§10.5.1), the connection between host star metallicity and the presence of small planets, and the planet formation process, is less clear, even with the Kepler data. While giant planets discovered by Kepler orbit metal-rich stars, F and G stars with small planets are not preferentially metal-rich (Schlaufman & Laughlin, 2011; Buchhave et al., 2012).

Buchhave et al. (2014) argued that the observed distribution of metallicity in more than 400 Kepler planet host stars revealed three distinct clusterings: terrestrial planets with  $R_p \leq 1.7R_\oplus$ , ‘gas dwarfs’ with  $1.7R_\oplus \leq R_p \leq 3.9R_\oplus$ , and ice or gas giants with  $R_p \geq 3.9R_\oplus$ . They suggested that these three populations formed via distinct planet formation channels. Schlaufman (2015) argued instead for a single continuous relationship between  $R_p$  and metallicity, suggesting that the planet formation process in a typical protoplanetary disk produces a continuum of planet sizes between  $1 - 4R_\oplus$ .

Zhu et al. (2016a) suggested that the planet–metallicity correlation is a power law below some critical saturation threshold, while the probability of hosting at least one planet is unity for stars above the threshold, and that stars with sub-solar metallicity are better targets for investigating the planet–metallicity correlation for small planets.

**Inferences from the solar system** Shu et al. (1993) had already noted that prevailing theories did not provide a natural explanation for the marked subdivision into the gas-rich (Jupiter/Saturn) and gas-poor (Uranus/Neptune) giants. To account for the observed differences in envelope to core mass would require special timing for the various formation phases (assemblage of the protoplanetary cores, runaway gas accretion, and nebular gas dispersal). They suggested that the primary H/He loss mechanism was photoevaporation by Lyman continuum photons in the outer parts of the disk. Saturn’s orbit then represented the transitional radius between gas retention and loss, and the evaporative wind in the Uranus–Neptune regions would have depleted the H/He before those planets gathered a critical core mass for runaway gas accretion. The hypothesis required that the primitive Sun had a high XUV luminosity over a period comparable to that of classical T Tauri stars. External (massive star) ionisation sources may also play a role (Desch, 2007; Mitchell & Stewart, 2010, 2011).

### 10.3.7 Observational constraints

Many observations, simulations, and interpretations of individual circumstellar disks have been made, and no attempt at completeness in the coverage of these topics is made here. High-angular resolution optical, infrared, and (sub-)mm facilities are the same as those used for probing transition disks and debris disks (§10.6.1). In particular, since the start of full operations in March 2013, ALMA (§7.12.2) is providing detailed structural, dynamical, and chemical insights across a range of protoplanetary, transition, and debris disks.

Key observations to validate developing numerical models include those probing disk structure on the scales of 1–10 au, where theory is most uncertain (e.g. Armitage, 2011; Gonzalez et al., 2015; Hall et al., 2016; Sicilia-Aguilar et al., 2016). As examples, potential planet-forming regions, as constraints on associated formation processes, have been studied in HR 4796A (Klahr & Lin, 2001), DR Tau (Brunngräber et al., 2016; Tazzari et al., 2016), and other disks with the highest spatial resolution achieved by ALMA, notably TW Hya, HL Tau, HD 163296, and DM Tau (e.g. Bergin et al., 2016; Boneberg et al., 2016; Zhang et al., 2016).

**Chemistry** In addition to the numerous physical and dynamical processes entering models of planet formation, chemical models of both the volatile composition (such as  $\text{H}_2\text{O}$ ,  $\text{CO}$ ,  $\text{CO}_2$ ), and refractory materials, are of great importance for the formation of rocky planets. The subject is considered more generally in Chapter 11.

Observations and modeling of the chemical composition and kinematics of protoplanetary disks is a broad research area which is only touched on here (cf. §10.2). Objectives include estimating the chemical composition of icy planetesimals and refractory condensates, identifying the many processes including gas–grain interactions (including photoevaporation and non-thermal desorption), the role of specific molecular tracers, and the characterisation of a large number of gas-phase molecules (including  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{CH}_4$ ,  $\text{NH}_3$ ,  $\text{HCO}$ ,  $\text{HCN}$ , and  $\text{CN}$ ), as well as a wide range of small but more complex organic molecules such as methanol,  $\text{CH}_3\text{OH}$ , and methyl formate,  $\text{HCOOCH}_3$  (e.g. Walsh et al., 2010; Ercolano & Owen, 2010; Eistrup et al., 2016; Parfenov et al., 2016; Walsh et al., 2016).

**Observations and models** Models of ice composition and refractory element formation yield the ice line (or snow line) positions for the different volatile species (§11.2.3), and allow the chemical composition and mass ratios of ices to rocks in icy planetesimals to be estimated throughout the protoplanetary disk (e.g. Marboeuf et al., 2014b,a; Thiabaud et al., 2014). For example, Marboeuf et al. (2014b) found that from an initial homogeneous nebula of solar chemical composition, a wide variety of planetesimal compositions were produced as a function of disk mass and radial distance. Ices incorporated into planetesimals are mainly  $\text{H}_2\text{O}$ ,  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{CH}_3\text{OH}$ , and  $\text{NH}_3$ , with an ice/rock mass ratio of  $1 \pm 0.5$ .

Yoneda et al. (2016) started from a cold (10 K) pre-stellar core, and used a radiation–hydrodynamic model to derive molecular compositions and distributions in the resulting protoplanetary disk through post-processing calculations of the gas–grain chemistry using a three-phase model. Stable molecules such as H<sub>2</sub>O, CH<sub>4</sub>, NH<sub>3</sub>, and CH<sub>3</sub>OH are already abundant at the onset of gravitational collapse, and sublimate as fluid parcels migrate inside the water snow line. Various carbon-chain and complex organic molecules are formed in the disk, with abundances dependent on photodissociation and diffusion. H<sub>2</sub>S ice is abundant in the collapse phase, while in the warmer disk regions, it is sublimated and destroyed, with SO, H<sub>2</sub>CS, OCS, and SO<sub>2</sub> becoming abundant.

The large optical depth of common molecules, such as CO and H<sub>2</sub>O (specifically as their most common isotopologue, thus <sup>12</sup>C<sup>16</sup>O), prevents probing the gas near the disk mid-plane. Rotational lines from rare molecules (specifically <sup>12</sup>C<sup>17</sup>O) may have ‘vertical’ optical depths near unity: strong enough to detect, yet transparent enough to trace the disk mid-plane, and yield estimates of the gas mass (Miotello et al., 2014; Yu et al., 2016; Molyarova et al., 2017).

**Dust composition** Modeling the often rich mid-infrared emission-line spectra also provides indications of the chemical composition of the dust. The literature is again substantial. As examples only, systems have been shown to comprise solid-state species such as complex tholins in HR 4796A (Debes et al., 2008); amorphous silica, silicate, and metal sulphides in HD 172555 (Lisse et al., 2009); forsterite in RECX 5 (Bouwman et al., 2010); crystalline and amorphous Mg-rich olivine and pyroxene in BP Pis (Melis et al., 2010a); and other primitive Kuiper-belt-like material in  $\eta$  Crv (Lisse et al., 2012).

The significant fraction of crystalline silicate material in comets, chondritic meteorites, and interplanetary dust particles indicates a modification of the almost completely amorphous interstellar medium dust from which they formed. Dust grain mineralogy (composition, amorphous-to-crystalline ratio, and grain size distribution) provides unresolved insights into the conditions under which crystalline silicates were formed, including details of the silicate sublimation front, temperature gradients and radial mixing (e.g. Oliveira et al., 2011; Roskosz et al., 2011; Saito & Sirono, 2011; Flock et al., 2016).

**C/O ratio** Of the major solid-forming elements, C and O abundances (and in particular the C/O abundance ratio) strongly affect the amounts of volatile ices and refractory phases in icy planetesimals, as a result of the partitioning of O among gas, refractory solid and ice phases in the final condensate. Thus, planetesimals formed in systems with sub-solar C/O should be water ice-rich, with lower than solar mass fractions of refractory materials, while in super-solar C/O systems planetesimals should have significantly higher mass fractions of refractories, in some cases having little or no H<sub>2</sub>O-ice (e.g. Johnson et al., 2012c). However, chemical processes in the protoplanetary disk mid-plane can modify the composition of ices and gases (e.g. Moriarty et al., 2014; Thiabaud et al., 2015b). Eistrup et al. (2016) concluded that in the inner disks at  $\lesssim 30$  au, interstellar ice abundances are preserved only if the ionisation level is low, or if these species are included in larger bodies within  $\sim 10^5$  yr.

**Dynamics** Dynamical insights from spectroscopy include evidence for a smooth transition between infalling matter and Keplerian rotation, e.g. in the CS ( $J = 7 - 6$ ) line in L1551 IRS5 (Chou et al., 2014), and in the C<sup>18</sup>O ( $J = 2 - 1$ ) and SO ( $J_N = 6_5 - 5_4$ ) lines in L1527 IRS (Ohashi et al., 2014).

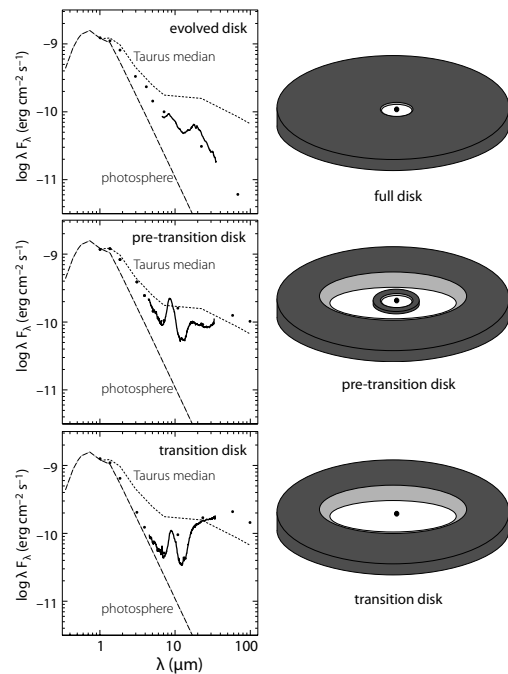


Figure 10.10: Disk types and schematics, from Espaillat et al. (2014, Figure 1). Left: spectral energy distributions of three K3–K5 stars illustrating an ‘evolved disk’, RECX 11 (top), a pre-transition disk, LkCa 15 (middle), and a transition disk, GM Aur (bottom). Relative to the Taurus median, an evolved disk has less emission at all wavelengths, a pre-transition disk has a mid-infrared deficit (5–20  $\mu\text{m}$ ), but comparable beyond the near-infrared, and a transition disk has deficits in the near- and mid-infrared with comparable emission at longer wavelengths. Right: disk geometries. The full disk has an inner wall (light grey) and outer disk (dark grey). Pre-transition disks have an inner wall and disk followed by a gap, then an outer wall and disk. Transition disks have an inner disk hole with an outer disk wall and disk. From *Protostars and Planets VI* edited by Henrik Beuther, Ralf S. Klessen, Cornelis P. Dullemond, and Thomas Henning. ©2014 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press.

**Orbital tilts** Possible effects of disk structure and dynamics on obliquities are considered in Section 10.10.7.

### 10.3.8 Transition disks

This section represents an observational ‘aside’. It details observational evidence for the appearance of gaps and cavities within protoplanetary disks, believed to correspond to the early stages of planet formation. Details of the particle and object growth underpinning terrestrial planet formation is resumed in Section 10.4.

**Introduction** The primordial phase of disk evolution ends with the dissipation of the gas, or gas clearing. This is typically completed within 1–6 Myr (§10.3.6), with 3 Myr often cited as a typical gas disk lifetime (Pascucci et al., 2006; Hernández et al., 2007b; Currie et al., 2009). Gas giants must form within this period.

In these later evolutionary stages of protoplanetary disks, but while still containing gas, inner gaps and cavities begin to appear in the dust distribution. These gaps are attributed to sculpting by embryonic planets, or in some cases to photoevaporation or other processes, substantially modifying the disk structure. Protoplanetary disks showing spectroscopic and morphological evidence for these inner holes and gaps are termed *transition disks*, conveying the idea of systems in the act of dispersing their residual planet-forming material and undergoing planet formation.

Further proposed sub-divisions (Figure 10.10) distinguishing *transition disks*, for which emission shortward of  $\sim 10 \mu\text{m}$  appears to be due entirely to optically-thin dust (Calvet et al., 2002, 2005), and *pre-transition disks*, with additional emission from warm optically-thick dust near the star (Espaillat et al., 2007, 2008, 2010, 2011).

Transition disks occupy an important observational phase in the evolution of protoplanetary disks. It is also inferred that dust growth, fragmentation and radial drift are strongly influenced by gas disk structure, with ‘pressure bumps’ suggested as key features that may allow grains to concentrate and grow efficiently (§10.4).

**Further classification** Complicating their definition and classification, the spectral energy distribution of some protoplanetary disks decreases with increasing wavelength. These have been referred to as ‘anaemic’ (Lada et al., 2006), ‘homologously depleted’ (Currie & Sicilia-Aguilar, 2011), ‘evolved’ (Hernández et al., 2007a, 2008, 2010; Espaillat et al., 2014), or ‘weak-excess transition’ (Muzerolle et al., 2010). Sometimes classed as transition disks, they comprise a mix of cleared inner disks, debris disks, and disks with significant dust grain growth and vertical settling (as in the ‘Butterfly star’, IRAS 04302+2247, Lucas & Roche, 1997; Wolf et al., 2003; Gräfe et al., 2013).

HD 166191 may be in transition between a full gas disk and a largely gas-free debris disk (Kennedy et al., 2014a), while a small number of *hybrid disks* appear to be gas-rich debris disks, with possible pristine gas of uncertain origin, along with secondary-generated dust (Péicaud et al., 2017).

**Infrared excess** Transition disks around young stars were originally recognised by their strong far-infrared ( $\geq 10 - 20 \mu\text{m}$ ) excess, but with significantly reduced fluxes compared to classical T Tauri disks at shorter (near- to mid-infrared) wavelengths (e.g. Strom et al., 1989; Calvet et al., 2002, 2005; D’Alessio et al., 2005; Espaillat et al., 2007, 2008; Fang et al., 2009; Gräfe et al., 2011; Owen & Clarke, 2012; van der Marel et al., 2016b).

**Disk clearing** The near- to mid-infrared emission deficit is generally attributed to the evacuation of the disk interior to 5–50 au (Marsh & Mahoney, 1992; Calvet et al., 2002; Rice et al., 2003c; Schneider et al., 2003; Calvet et al., 2005; Espaillat et al., 2007, 2008; Hughes et al., 2009; Espaillat et al., 2010), an interpretation confirmed in some cases by direct sub-mm imaging (e.g. Piétu et al., 2006; Brown et al., 2007, 2009; Andrews et al., 2009; Hughes et al., 2009; Andrews et al., 2011b).

High-contrast optical imaging has provided direct morphological evidence for gaps and related structures (see below). They are often attributed to various manifestations of disk–planet interaction (e.g. Paardekooper & Mellema, 2004; Quillen et al., 2004; Alexander & Armitage, 2009; Krijt & Dominik, 2011; Perez-Becker & Chiang, 2011; Zhu et al., 2011; Kraus & Ireland, 2012; Pinilla et al., 2012a; Tanigawa et al., 2012; Zhu et al., 2012b; Clarke & Owen, 2013; Dong & Dawson, 2016).

Other suggested disk-clearing mechanisms include grain growth leading to a drop in optical depth (Dullemond & Dominik, 2005; Tanaka et al., 2005; Birnstiel et al., 2012a); magnetorotational instabilities (Chiang & Murray-Clay, 2007; Dominik & Dullemond, 2011); photoevaporation (Alexander & Armitage, 2007; Clarke, 2007; Ercolano et al., 2008); and truncation by close stellar companions (Ireland & Kraus, 2008; Lestrade et al., 2011). Mapping the dust grain size throughout the disk can indicate which of these contributes in any given system (e.g. Hornbeck et al., 2016).

Several transition disks show signs of ongoing accretion (e.g. Fang et al., 2009; Sicilia-Aguilar et al., 2010), indicating that some gas is streaming through these opacity holes (e.g. Dominik & Dullemond, 2011; Perez-Becker & Chiang, 2011; Zhu et al., 2012b; Müller & Kley, 2013).

Alexander & Armitage (2009) predicted that young transition disks are more likely to host embedded giant planets, while older transition disks are more likely to be undergoing disk clearing.

**Angular scales** Observationally, transition disks are well represented in nearby star-forming regions such as Ophiuchus, Taurus and Upper Scorpius (e.g. Currie & Sicilia-Aguilar, 2011; Espaillat et al., 2011; Chen et al., 2012; Mathews et al., 2012b,a; Mayama et al., 2012; Orellana et al., 2012; Rizzuto et al., 2012; Najita et al., 2015). Most of the inferred disk-clearing processes take place in the inner few au, i.e. on scales  $\rho \leq 0.01$  arcsec, even for young nearby stars.

Since these angular scales are inaccessible to conventional imaging, earlier studies relied mostly on the modeling of spatially-unresolved spectral energy distributions. However, these suffer from degeneracies: grain temperature, for example, is sensitive to distance from the star, particle size, and dust composition (Thamm et al., 1994; Vinković et al., 2003). Multi-wavelength interferometry has addressed some of these degeneracies (e.g. Kraus et al., 2010; Melis et al., 2011a; Wolf et al., 2012; Kraus et al., 2013; Willson et al., 2016).

**Morphology** High-contrast imaging (§7.9.2) is providing direct evidence for structural features such as gaps, rings, and probable protoplanets. Discoveries have been made in reflected light with both ‘first-generation’ (e.g. VLT-NACO and Keck-NIRC2) and ‘second-generation’ instruments (including Gemini-GPI, VLT-SPHERE and Subaru-HiCIAO), as well as SMA, ALMA and Herschel

(see also §7.9), with further diagnostics available from polarimetry (e.g. Hashimoto et al., 2012; Quanz et al., 2013b; Avenhaus et al., 2014a; Rodigas et al., 2014b).

The related literature, both observational and theoretical, is substantial. The following gives an orientation, with recent reviews providing details (e.g. Williams & Cieza, 2011; Espaillat et al., 2014; Wyatt et al., 2015; Owen, 2016; Casassus, 2016; Ercolano & Pascucci, 2017).

Objects with prominent gaps seen in direct imaging include PDS 70 (Hashimoto et al., 2012; Dong et al., 2012; Hashimoto et al., 2015), TW Hya (e.g. Trilling et al., 2001; Wilner et al., 2003; Apai et al., 2004a; Debes et al., 2013; Qi et al., 2013b; Akiyama et al., 2015; Rapson et al., 2015; Debes et al., 2016; Nomura et al., 2016; Uyama et al., 2017b), and HD 166191 which may be in transition between a full gas disk and a largely gas-free debris disk (Kennedy et al., 2014a). Prominent rings have been observed with VLT-SPHERE and ALMA in RX J1615 (de Boer et al., 2016), and HD 97048 (Ginski et al., 2016b; van der Plas et al., 2017).

Near-infrared imaging also reveals prominent spiral structure (Figure 7.30), some with evidence of embedded protoplanets, e.g. HD 100453 (Wagner et al., 2015a; Dong et al., 2016c; Benisty et al., 2017; Long et al., 2017); HD 100546 (e.g. Benisty et al., 2010; Quanz et al., 2013a; Avenhaus et al., 2014a; Pineda et al., 2014; Walsh et al., 2014; Quanz et al., 2015a; Currie et al., 2015; Garufi et al., 2016; Lyra et al., 2016; Follette et al., 2017); HD 135344B (Lyo et al., 2011; Muto et al., 2012; Sitko et al., 2012; Garufi et al., 2013; Carmona et al., 2014; Pérez et al., 2014; Bae et al., 2016b; van der Marel et al., 2016a; Maire et al., 2017); HD 142527 (Biller et al., 2012; Rameau et al., 2012; Avenhaus et al., 2014b; Rodigas et al., 2014b; Marino et al., 2015; Lacour et al., 2016; Montesinos et al., 2016; Owen & Lai, 2017; Soon et al., 2017); MWC 758 (Grady et al., 2013); and Oph IRS 48 (Follette et al., 2015).

**Observations at mm wavelengths** At mm wavelengths, at resolution  $40 \times 20 \text{ mas}^2$ , ALMA imaging of HL Tau shows a ring system (Figure 7.34) which has been extensively analysed (Brogan et al., 2015; Testi et al., 2015; Akiyama et al., 2016; Demidova & Shevchenko, 2016; Jin et al., 2016; Matsakos et al., 2016; Okuzumi et al., 2016; Pinte et al., 2016; Takahashi & Inutsuka, 2016; Boley, 2017; Hasegawa et al., 2017; Liu et al., 2017d; Simbulan et al., 2017; Stephens et al., 2017; Yen et al., 2017). Longer wavelength radio observations with the VLA (Carrasco-González et al., 2016) indicate fast grain growth, fragmentation, and formation of dense clumps in the inner parts of the disk, suggesting that the HL Tau disk may be in a very early stage of planetary formation, with planets not already formed in the gaps but in the process of future formation in the bright rings. Similar structure is seen in Sz 91 (Canovas et al., 2015, 2016).

Sub-mm continuum asymmetries may indicate dust traps triggered by vortices acting as azimuthal pressure

**Dipper stars and dipper disks:** Inner protoplanetary disks are being probed by the new class of *dipper stars*. These have optical and infrared light curves with episodic drops in flux consistent with extinction by transiting dusty structures (disk warps, vortices, and forming planetesimals) with Keplerian periods down to a few days.

Dipper stars were first identified from CoRoT and Spitzer data in the young ( $\sim 2\text{--}3$  Myr) Orion Nebula Cluster (Morales-Calderón et al., 2011) and NGC 2264 region (Alencar et al., 2010; Cody et al., 2014). They showed depth, duration, and periodicity consistent with dust orbiting near the star-disk co-rotation radius. McGinnis et al. (2015) proposed that dippers in NGC 2264 could be explained by occulting inner disk warps driven by accretion streams.

Ansdell et al. (2016a) identified 25 dippers in the young ( $\leq 10$  Myr) Upper Sco and  $\rho$  Oph star-forming regions using K2 data, which they attributed to occulting vortices at the inner disk edge produced by Rossby wave instability and transiting clumps of circumstellar material, viewed edge-on. Ansdell et al. (2016b) used archival sub-mm observations of three of them (EPIC 204638512 which hosts the face-on transition disk J1604–2130, EPIC 205151387, and EPIC 203850058) to argue that nearly edge-on disks are not a defining characteristic. Further studies are continuing to clarify their nature (e.g. Scaringi et al., 2016; Rodriguez et al., 2017a; Bodman et al., 2017; Hedges et al., 2018).

bumps (e.g. Johansen et al., 2011; Lyra & Lin, 2013; Birnstiel et al., 2013; Owen, 2014a; Zhu & Stone, 2014).

**Shadows** Unlike thermal imaging (e.g. with ALMA), imaging in scattered light relies on light from the central star reaching the disk surface. As a result, appearance of the outer disk is sensitive to shadowing effects of the otherwise unresolved inner disk. Light travel time effects can also be significant: for an opaque clump orbiting within 1 au, with significant orbital motion during the light travel time from the clump to the outer disk, the delay in light rays reaching the sky plane can give rise to a various spiral- and arc-shaped shadows (Kama et al., 2016; Montesinos & Cuello, 2018).

Such *shadows* have been used to infer structure in the inner (unresolved) disk. Thus TW Hya was found to display small inner warps (Debes et al., 2017), while in HD 142527 (Marino et al., 2015; Montesinos et al., 2016) and HD 100453 (Benisty et al., 2017; Long et al., 2017; Min et al., 2017), the inner disk is sufficiently misaligned that two clear shadow lanes appear on the outer disk.

**Misaligned inner and outer disks** Such misalignments between inner and outer disks may be generated through a secular resonance between the nodal precession of the inner disk and the precession of the gap-opening companion (Owen & Lai, 2017). An evolving protostellar system may naturally cross this resonance during its lifetime due to disk dissipation and/or companion migration. If resonance crossing occurs on the appropriate time scale, of order a few Myr, the inner and outer disks can become highly misaligned, with misalignments  $\geq 60^\circ$  typical.

**Evidence for planets** High-contrast imaging is providing more direct evidence for the existence of (proto-)planets within protoplanetary disk gaps, e.g. in the cases of T Cha (Huélamo et al., 2011; Cieza et al., 2011); LkCa 15 (e.g. Bonavita et al., 2010; Thalmann et al., 2010; Kraus & Ireland, 2012; Isella et al., 2012; Thalmann et al., 2014b; Sallum et al., 2015); and HD 169142 (Quanz et al., 2013b; Osorio et al., 2014; Biller et al., 2014; Reggiani et al., 2014; Wagner et al., 2015b; Fedele et al., 2017; Macías et al., 2017; Pohl et al., 2017a). Searches for structural perturbations due to embedded planets can also be made using spectral line tracers such as CO (Regály et al., 2010; Bast et al., 2011; Hales et al., 2014).

**Models** Both vortices and spirals may indicate the presence of recently formed massive planets: in the case of vortices, through Rossby wave instability at the steep edges of the gap carved by the planet (Lovelace et al., 1999; de Val-Borro et al., 2007; Regály et al., 2012; Barge et al., 2017), and in spirals, through the triggering of density waves directly by the (proto-)planet (e.g. Dong et al., 2011b,a; Kim & Taam, 2012; Kley & Nelson, 2012; Dong et al., 2015a; Richert et al., 2015; Bae et al., 2016a; Lyra et al., 2016; Rafikov, 2016; Bae et al., 2017).

In addition to density waves and shadows, other explanations for spiral arms in young disks include gravitational instabilities (e.g. Rice et al., 2004; Lodato & Rice, 2004, 2005; Williams & Cieza, 2011), Rossby wave instability at the edge of a dead zone (e.g. Lyra et al., 2015), accretion (e.g. Lesur et al., 2015), or a result of viewing geometry (Dong et al., 2016a).

Ayliffe et al. (2012) showed that planets with  $M_p \geq 0.3M_J$  can open sufficiently deep gaps in the gas disk to trap inwardly spiraling meter-sized solid bodies in the density maximum at the gap's outer edge. At  $\sim 1M_J$  bound clumps of solid material, as large as several  $M_\oplus$ , may form, potentially collapsing under self-gravity to form planets or planetesimals. In this way, the formation of a second generation of planetesimals or of terrestrial mass planets may be triggered by the presence of a high-mass planet (Lyra et al., 2009; Ayliffe et al., 2012).

Other simulations of (gas and dust) gaps under various (quiescent and turbulent) gas and disk conditions have been made, some showing multiple disk gaps and other complex structures (e.g. Jang-Condell & Turner, 2012, 2013; Duffell & MacFadyen, 2013; Fung et al., 2014; Morbidelli et al., 2014; Dong et al., 2015b; Kanagawa et al., 2015b; Carballido et al., 2016; Dipierro et al., 2016; Fung & Chiang, 2016; Lee, 2016; Ruge et al., 2016; Carballido et al., 2017; Chametla et al., 2017; Dipierro & Laibe, 2017; Dong et al., 2017c; Kanagawa et al., 2017).

Wide inner holes of  $\geq 15$  au are possibly only sculpted by *multiple planets* inside each hole (Dodson-Robinson & Salyk, 2011; Zhu et al., 2011; Duffell & Dong, 2015). Polarised emission versus gap structure and inclination angle was modeled by Jang-Condell (2017).

Methods of estimating planet masses from the observed gap structures are also ongoing (Fung & Dong, 2015; Kanagawa et al., 2015a, 2016; Rosotti et al., 2016; Dong & Fung, 2017a,b). As an example, Uyama et al. (2017b) estimated masses of  $1.45M_J$  at 25 au and  $2.29M_J$  at 95 au as responsible for the multi-ring disk in TW Hya.

**Abundances** Abundances and their radial dependencies can be reconstructed from 2d spectrophotometry. Again, as an example only, the location of the snow line at 4.2 au in TW Hya has been reconstructed from a combination of Spitzer-IRS, Herschel-PACS, and Herschel-HIFI spectra (Zhang et al., 2013b), and the CO snow line imaged with ALMA, in the  $N_2H^+$  diazenylium ion (in its 1–0 rotational transition at 93.174 GHz), revealed as a disk of radius of 30 au (Qi et al., 2013b).

## 10.4 Terrestrial planet formation

The previous section has provided an overview of the many complex processes which are believed to operate within protoplanetary disks, and which complicate any simple picture of progressive particle growth. In this section, these complexities are largely put to one side, and the various processes believed to underpin growth, from sub- $\mu\text{m}$  particles up to planetary mass, are described.

### 10.4.1 Stages in formation

Many of the basic ideas central to the current picture of terrestrial planet formation were presented by Safronov (1969), and in its English translation (Safronov, 1972), and have been refined subsequently (e.g. Goldreich & Ward, 1973; Cameron, 1973; Wetherill, 1990; Lissauer, 1993, 1995; Wetherill, 1996; Bodenheimer, 2006).

In this 'bottom-up' picture, planet formation occurs in a number of successive stages (Figure 10.4): (i) dust settles into the mid-plane of the system; (ii) collisional processes and instabilities in the dust disk build up larger bodies of km size and larger called 'planetesimals' (box, page 455); (iii) planetesimals merge (or otherwise accrete) to form either terrestrial planets or, further out in the disk, more massive cores of the giant planets; (iv) the giant planet cores acquire a gaseous envelope.

Very broadly, and over the past two decades, the picture of planet formation driven by  $\alpha$  viscosity accretion has developed into a paradigm involving wind-driven accretion, magnetorotational and streaming instabilities, dead zones, transition disks, and planet-disk interactions (§10.3). Growth mechanisms involve 'sticking' at the smallest mass scales, gravoturbulence, fractal growth, and dust traps for medium-sized particles, and gravity domination on the largest mass scales.

Developing reviews give further details and perspectives (e.g. Thommes, 2007; Alibert et al., 2010; Raymond, 2010; Morbidelli et al., 2012a; Raymond et al., 2014). Others cover the later stages of planetary migration and long-term dynamical evolution (e.g. Thommes & Lissauer, 2005; Masset & Kley, 2006; Papaloizou & Terquem, 2006; Kley & Nelson, 2012; Davies et al., 2014).

### 10.4.2 Dust to rocks: sub-micron to 10 m

Within the complex environment within protoplanetary disks (§10.3), dust grains are presumed to settle into a dense layer towards the disk mid-plane, where they begin to stick together through a combination of electrostatic forces and collisional impacts, growing as they collide (Kusaka et al., 1970). The smallest particles collide gently due to Brownian motion, while larger aggregates achieve progressively higher collision speeds as they gradually decouple from the smallest eddies of the turbulent gas flow.

Micron-sized nebula dust would probably take too long to settle into the disk mid-plane, even in the absence of turbulence (Dullemond & Dominik, 2004; Johansen & Klahr, 2005; Carballido et al., 2005; Fromang & Papaloizou, 2006; Turner et al., 2006, 2007). Weidenschilling et al. (1989) accordingly constructed models in which the dust particles form larger entities that would settle more quickly. Their models suggest that the resulting dust structures would be looser than the dense-packed  $m \propto d^3$ , and with their predicted  $m \propto d^2$  structures, a settling time scale of  $10^5 - 10^6$  yr was estimated.

While small  $\mu\text{m}$ -sized grains closely follow the gas density, larger particles gradually decouple from the gas flow and fall towards the mid-plane. An equilibrium mid-plane layer is formed when the turbulent diffusion of the particles (e.g. as driven by magnetorotational instability) balances the rate of sedimentation (e.g. Dubrulle et al., 1995; Johansen & Klahr, 2005; Turner et al., 2006; Johansen et al., 2014).

Progressive aggregation, assisted by the various concentration mechanisms, believed to operate in protoplanetary disks and considered in Section 10.3, is then believed to form macroscopic objects, or ‘rocks’, with sizes  $\sim 0.01\text{--}10$  m, somewhat analogous to the rings around Saturn (§12.5.12).

**Particle growth** Many modeling efforts have examined the interaction and growth of particles, including the effects of aggregation, compactification, and collisions. An illustration of the type of simulations undertaken is shown in Figure 10.11.

Three basic types of collisional interactions between dust aggregates are generally recognised: direct collisional sticking, in which two dust aggregates collide gently enough for contact forces to bind the aggregates together; ‘bouncing’, for intermediate particle sizes; and fragmentation (including erosion), in which high collisional energy results in the break-up of dust aggregates.

A classification of collision data in terms of four fragment populations (the largest and second largest fragment, a power-law population, and a sub-resolution population) was developed and modeled by Geretshauser et al. (2011a,b).

Many of these considerations apply from the smallest dust particles upwards in size, into the growth step

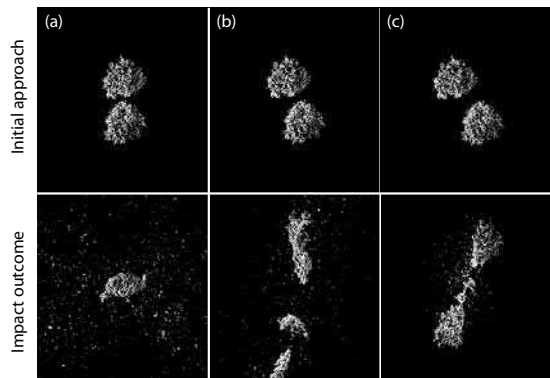


Figure 10.11: Collisional outcomes (lower panels) of ballistic particle-cluster aggregation simulations, using clusters of 8000 ice particles. Initial aggregates (upper panels) collide vertically, at  $70 \text{ m s}^{-1}$ , with (a–c) illustrating increasing normalised impact parameter 0.00, 0.39, and 0.69, respectively. From Wada et al. (2009, Figure 2), by permission of IOP Publishing/AAS.

from cm-sized pre-planetesimals to km-sized planetesimals, although a number of effects considered below further complicate these later growth stages. Specifically, the formation of larger objects from the highly porous pre-planetesimals may be halted by a combination of fragmentation in disruptive collisions and mutual rebound with compaction (Blum & Wurm, 2008; Brauer et al., 2008a; Lambrechts & Johansen, 2012).

Formation of a dust disk within the lifetime of the nebula disk is, nevertheless, a prerequisite. The inference of mm-sized grains in the terrestrial zone of the 3 Myr old protoplanetary disk of KH 15D provides the type of observational support helping to corroborate such theories (Herbst et al., 2008).

**Laboratory studies** Collisional experiments in the laboratory have resulted in detailed physical models for the collisional behaviour of silicate aggregates over a wide range of mass, mass ratios and porosities (e.g. Supulver et al., 1997; Blum & Wurm, 2000; Blum, 2000; Wurm & Blum, 2006; Güttler et al., 2010; Kothe et al., 2010; Zsom et al., 2010; Brucato & Nuth, 2010; Zsom et al., 2010; Beitz et al., 2011; Teiser et al., 2011a,b; Zsom et al., 2011a; Jankowski et al., 2012; Meisner et al., 2012; Schräpler et al., 2012; Deckers & Teiser, 2013; Duermann et al., 2013; Kothe et al., 2013; Meisner et al., 2013; Deckers & Teiser, 2014; Kelling et al., 2014; Testi et al., 2014; Deckers & Teiser, 2016; Kruss et al., 2016; Musiolik et al., 2016; Katsuragi & Blum, 2017; Kruss et al., 2017).

Experiments have also been carried out under microgravity, using the (9-s duration) Bremen drop tower in 2011 (Brisset et al., 2017), the sub-orbital REXUS 12 in 2012 (Brisset et al., 2016), on the Space Shuttle (Blum et al., 2000), and on the International Space Station (Love et al., 2014).

**Simulations and complexities** Uncertainties arise from the complex physics, including dependencies on composition, bulk density and fractal dimension, tensile strength, particle rotation, opacities, electric charge and repulsion effects, vertical settling, collisional obliqueness, mass ratio, and dust regeneration (e.g. Weidenschilling, 1980; Dominik & Tielens, 1997;



Sekiya, 1998; Goodman & Pindor, 2000; Dullemond & Dominik, 2005; Henning et al., 2006; Johansen et al., 2006a; Dominik et al., 2007a; Johansen et al., 2007; Blum & Wurm, 2008; Johansen et al., 2008; Wada et al., 2009; Blum, 2010; Youdin, 2010; Geretshauser et al., 2011a; Kelling & Wurm, 2011; Okuzumi et al., 2011a,b; Ilgner, 2012; Jontof-Hutter & Hamilton, 2012a,b; Okuzumi et al., 2012; Pinilla et al., 2012b; Garaud et al., 2013; Kataoka et al., 2013a; Ma et al., 2013; Wada et al., 2013; Cuzzi et al., 2014; Laibe et al., 2014a; Laibe, 2014; Laibe et al., 2014b; Ormel, 2014; Krijt et al., 2015; Arakawa & Nakamoto, 2016).

**Aggregate compression** Changes in porosity (or volume filling factor) due to collisional impacts involve the rolling motion between constituent particles, governed by the *rolling energy*, and the *fractal dimension* of the particles. The latter quantifies their surface structural complexity, and is typically in the range 2–3 (e.g. Filippov et al., 2000; Paszun & Dominik, 2009).

Various models and N-body simulations of sequential collisions have been reported (e.g. Ormel et al., 2007; Wada et al., 2007; Suyama et al., 2008; Wada et al., 2008; Weidling et al., 2009; Okuzumi et al., 2012; Seizinger et al., 2012; Suyama et al., 2012; Kataoka et al., 2013b,a; Meru et al., 2013b; Gunkelmann et al., 2016). Aggregates are also compressed by ram pressure of the gas disk, to  $\rho \sim 10^{-3} \text{ Mg m}^{-3}$  (Kataoka et al., 2013a).

Further compaction as a result of self-gravity occurs at higher masses (§10.4.7), with indicative densities of  $\rho \sim 10^{-1} \text{ Mg m}^{-3}$  at  $R \sim 10 \text{ km}$  (Wada et al., 2008, 2009; Kataoka et al., 2013a).

**Bouncing barrier** Bouncing (or rebound) events have been observed frequently in laboratory experiments (e.g. Blum & Münch, 1993; Langkowski et al., 2008; Weidling et al., 2009, 2012), and subsequently incorporated into N-body simulations of aggregate collisions (Wada et al., 2011; Seizinger & Kley, 2013).

Since bouncing does not lead directly to further mass gain, the growth of dust aggregates is inhibited at the resulting *bouncing barrier*, a phenomenon reproduced by detailed numerical simulations (Zsom et al., 2010; Windmark et al., 2012a,b). For a minimum-mass solar nebula model at 1 au, the maximum dust aggregate size is in the range of mm to cm.

Above the ‘bouncing barrier’, growth has been found to continue by *mass transfer* in high-speed collisions (Wurm et al., 2005; Johansen et al., 2008; Güttler et al., 2010; Zsom et al., 2010; Windmark et al., 2012a; Johansen et al., 2014). For example, Windmark et al. (2012a) showed that, at 3 au, cm-sized seeds can sweep up mm-sized particles stuck at the bouncing barrier, growing to 3 m in  $10^5 \text{ yr}$ , and to 100 m in  $10^6 \text{ yr}$ .

However, on its own, such mass transfer does not appear to lead to widespread planetesimal formation, other than perhaps in the innermost part of the protoplanetary disk where dynamical time-scales are short.

Highly porous and low-speed icy aggregates may also grow beyond the bouncing and radial drift barriers due to efficient sticking combined with cross sections enhanced by a low internal density (e.g. Wada et al., 2008, 2009; Windmark et al., 2012b; Garaud et al., 2013; Kataoka et al., 2013a; Seizinger & Kley, 2013).

**Collision speeds and fragmentation** Beyond the bouncing barrier, the next obstacle occurs when collisional velocities reach the fragmentation velocity of  $\sim 1 \text{ m s}^{-1}$ , and collisions between two similar-sized silicate dust particles fragment rather than accrete. Consequently, growth will stall and the size distribution will, as with the bouncing case, settle into some steady state (e.g. Birnstiel et al., 2010, 2011, 2012b,a; Booth & Clarke, 2016).

In the framework of turbulent particle growth, the collision speed is central to numerical modeling (e.g. Johansen et al., 2014). But at close separations, when the particles are about to collide, they interact with the same eddies, and their motions are highly correlated. In turn, this requires estimates of the speed and power spectrum of the eddies, along with the gravitational effects of the turbulent gas density fluctuations (e.g. Voelk et al., 1980; Laughlin et al., 2004b; Nelson & Papaloizou, 2004; Ormel & Cuzzi, 2007; Pan & Padoan, 2010; Hubbard, 2013a; Pan & Padoan, 2014; Homann et al., 2016; Hopkins, 2016a).

**Coagulation equation** A quantitative approach to describing the size evolution of a number of merging bodies is based on the *coagulation equation*, or Smoluchowski equation (Smoluchowski, 1916), which describes the evolution of the mass spectrum of a collection of particles due to successive mergers. In discrete form, the bodies are represented as integer multiples of a small mass  $m_1$ , with  $n_k$  bodies of mass  $m_k = km_1$  at time  $t$ . Neglecting fragmentation

$$\frac{dn_k}{dt} = \frac{1}{2} \sum_{i+j=k} A_{ij} n_i n_j - n_k \sum_{i=1}^{\infty} A_{ki} n_i, \quad (10.14)$$

where  $A_{ij}$  is the rate of mergers between bodies of mass  $m_i$  and  $m_j$ , including effects such as gravitational focusing. The first term represents the increase in the number of bodies of mass  $m_k$  due to collisions of all pairs of bodies whose masses  $m_i, m_j$  sum to  $m_k$ , while the second term describes the loss of masses  $m_k$  due to their incorporation into larger bodies.

It has been applied to simulations over a wide range of masses, including dust particles, but with outcomes depending very strongly on the assumed underlying physics of internal structure (porosity and fractal exponent), composition, and fragmentation (e.g. Windmark et al., 2012a; Garaud et al., 2013; Paruta et al., 2016).

Implementation of the coagulation equation can incorporate gas drag, Poynting–Robertson drag, radiation pressure, and collisional fragmentation to treat the growth of planetesimals into oligarchs, with perturbations of eccentricity and inclination and explicit N-body calculations introduced to follow the evolution of oligarchs into planets (Safronov, 1969; Safronov, 1972; Wetherill & Stewart, 1993; Kenyon & Luu, 1998; Lee, 2000; Inaba et al., 2001; Bromley & Kenyon, 2006).

Large-scale Monte Carlo simulations have also been undertaken (Ormel et al., 2007; Ormel & Spaans, 2008; Zsom & Dullemond, 2008; Zsom et al., 2010, 2011a). A comparison of the two approaches, and preference regimes, is given by (Drazkowska et al., 2014). A combination of N-body and (Fokker–Planck-type) statistical techniques has also been developed (Glaschke et al., 2014; Amaro-Seoane et al., 2014).

#### 10.4.3 Rocks to planetesimals: 10 m to 10 km

Over the next  $10^4 - 10^5$  years, further growth is believed to lead to the formation of *planetesimals*, objects of size  $\sim 1$  km and above (box, page 455). This may occur through a continuation of the same type of pairwise collisional growth as at smaller size scales (although see Section 10.4.4). Gravitational interactions between individual bodies remain very weak until, by definition, the minimum planetesimal mass is achieved. The planetesimal formation stage is believed to extend to sizes where the escape speed of the largest bodies exceeds the random motion of the planetesimals to enter the next stage of gravity-driven collisions.

Once of planetesimal size, the bodies are largely decoupled from the gas (by definition), and their evolution can subsequently be modeled analytically or by N-body simulations. In this regime, Safronov (1972) showed that if the random relative velocity between planetesimals is less than the escape speed from the largest of them, then that body will grow at the expense of the others, accreting all other bodies that collide with it.

Planetesimals must grow to run-away sizes despite bouncing or disruptive collisions, and they must grow rapidly, constrained by radial drift time-scales of cm- to m-sized particles as short as a few hundred orbits. For dusty bodies up to 10 km size approaching closer than  $\sim 0.4$  au to the star, disruption may also occur by *thermophoresis* due to internal thermal gradients driven by the solid-state greenhouse effect (Wurm, 2007).

Despite these difficulties there is good evidence from cosmochemistry that large planetesimals formed in the solar nebula within a few Myr, early enough to melt and differentiate through the decay of short-lived radionuclides (e.g. Kleine et al., 2004a; Baker et al., 2005; Moskovitz & Gaidos, 2011; Neumann et al., 2012; Šrámek et al., 2012).

Newly-formed planetesimals move on elliptical orbits, and with gravitational interactions between them, equivalent to elastic collisions, increasing their random motions. Eventually, this increase in relative velocities and orbital eccentricities increases the probability of inelastic conditions, which damp the random component of the motions. A balance between the two effects occurs when the mean random velocity is of the order of the escape velocity from the largest planetesimal.

The protoplanet then grows at a rate given by (Pollack et al., 1996, eqn 1)

$$\frac{dM_e}{dt} = \pi R_c \Sigma_p \Omega F_g, \quad (10.15)$$

where  $M_e$  is the embryo mass,  $R_c$  is its effective or capture radius,  $\Sigma_p$  is the surface mass density of planetesimals,  $\Omega$  is the orbital frequency, and  $F_g$  is the gravitational enhancement factor given by the ratio of the gravitational to geometric cross sections. For Keplerian motion,  $\Omega \propto r^{-3/2}$ , and the time scale for planet growth increases steeply with increasing  $r$  as a consequence of the dependence of  $\Omega$  on  $r$ , and because  $\Sigma_p$  is expected to decrease with increasing  $r$ .

For plausible models of disk mass of order  $0.1 M_\odot$ , and a surface density varying as  $r^{-1}$ , total formation times estimated from such models would be of order  $4 \times 10^6$  yr for the Earth ( $r = 1$  au,  $\Sigma \sim 10^3$  kg m $^{-2}$ );  $5 \times 10^8$  yr for a  $10 M_\oplus$  Jupiter core ( $\Sigma \sim 200$  kg m $^{-2}$ ); and  $3 \times 10^{10}$  yr for Neptune ( $\Sigma \sim 30$  kg m $^{-2}$ ), the latter greatly exceeding the age of the solar system. Since the lifetimes of nebula disks are of order a few million years at most, local enhancements of the surface density, or a reduction in the relative planetesimal velocities, are required to reduce the formation time scales to plausible durations.

In numerical simulations, protoplanetary growth proceeds in several different regimes, depending on the dynamical state of the planetesimal disk. If the growth of the velocity dispersion is dominated by the embryos, and assuming that gravitational focusing is weak, then (e.g. Rafikov, 2003a, eqn 3)

$$\frac{1}{M_e} \frac{dM_e}{dt} \propto M_e^{-1/3}, \quad (10.16)$$

and embryo growth slows as its mass increases. Such *orderly growth*, characterised by very long time scales of order  $10^8 - 10^9$  yr (Safronov, 1972), implies that many embryos would grow at roughly the same rate, although in the simulations of Rafikov (2003a), for example, such orderly growth never develops.

Collisional outcomes during growth from planetesimals to planets span multiple regimes, and involves cratering, merging, disruption, super-catastrophic disruption, and hit-and-run events. Scaling laws to demarcate the transition between collision regimes, and to describe the size and velocity distributions of the post-collision bodies, are given by Leinhardt & Stewart (2012); Stewart & Leinhardt (2012).

Meanwhile, planetesimals with radii 1–1000 km and beyond may continue to accrete dust in low turbulence disk regions (Xie et al., 2010a; Guillot et al., 2014a).

**Binary planetesimals** Many binary planetesimals are observed in the solar system (§12.5), suggesting a high occurrence rate more generally. Gravitational encounters of binary planetesimals can have an important role in the evolution of planetesimal disks, catalysing close encounters, enhancing their

collision rate, and providing an additional heating source of the planetesimal disk through potential energy exchange (Donnison, 2010a; Perets, 2011; Quillen et al., 2012). During the residual gas phase, their dynamics and survival is also influenced by differential gas dynamical friction and wind-shearing drag (Perets & Murray-Clay, 2011; Grishin & Perets, 2016).

**Time scale for growth to 10 km** Growth over the meter-size barrier of 0.01–10 m, perhaps extending up to  $10^4$  m, remains particularly uncertain for the various reasons noted, with corresponding uncertainties on associated formation time scales. Growth to 0.01 m may require as little as  $\sim 10^3$  yr, with growth from 0.01– $10^4$  m requiring somewhere in the range  $10^3$ – $10^6$  yr (Rice et al., 2006; Brauer et al., 2008a; Johansen et al., 2008).

#### 10.4.4 Pebbles as primary building blocks

Models of protoplanetary dust growth have been challenged by the halting of growth at cm-sizes due to the occurrence of ‘bouncing’ at velocities of  $\geq 0.1 \text{ m s}^{-1}$ , and by particle fragmentation at velocities  $\geq 1 \text{ m s}^{-1}$ . To overcome these barriers, models based on *pebble accretion* have been developed. These are based on the formation of cm-sized dust pebbles by coagulation, followed by their spatial concentration by the types of mechanisms described in Section 10.3.5, followed by their subsequent gravitational collapse.

Observationally, pebble accretion models build on the inferred existence of pebble-sized particles from dust continuum observations of young circumstellar disks around low-mass pre-main-sequence stars, which show growth of the dominant particle size to mm- or cm-sizes within less than 1 Myr (Testi et al., 2003; Wilner et al., 2005; Rodmann et al., 2006).

Following the formation of a large number of small pebbles in the protoplanetary disk, with sizes limited by the ‘bouncing barrier’, self-gravitating concentrations of pebbles form in the turbulent gas and overdense filaments (e.g. Rafikov, 2004; Johansen et al., 2007, 2009b; Kenyon & Bromley, 2009; Kato et al., 2012).

In later growth stages, and in contrast to the earlier picture of larger bodies resulting from planetesimal pairwise collisions, it is much more favourable for an existing planetesimal to capture smaller (cm- to m-sized) particles (or ‘pebbles’) from within its Hill sphere than to interact with other planetesimals (Figure 10.12). In this picture, cm-sized pebbles may be the primary building blocks of planetesimals, both inside the ice line (the present-day asteroids) and outside it (present-day comets and Kuiper belt objects).

Early investigations into the accretion of pebble-sized particles onto protoplanets (Ormel & Klahr, 2010; Johansen & Lacerda, 2010), showed that they can be accreted from the core’s entire Hill sphere, leading to a prograde particle disk, which in turn could explain asteroid spin periods, and the preferentially prograde spin of

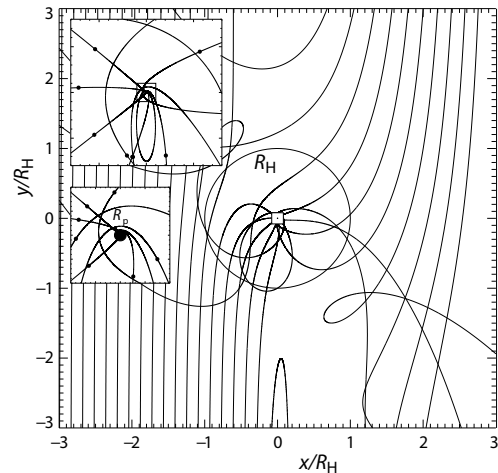


Figure 10.12: Pebble accretion in the Hill regime. Very large pebbles that couple to the gas on a time-scale much longer than the orbital time-scale (lighter grey lines) are scattered by the protoplanet. Optimally-coupled pebbles with Stokes number  $Stk=1$  (solid lines) are accreted from most of the Hill radius (box, page 512). Trajectories of strongly-coupled pebbles ( $Stk=0.1$ ), shown in the original figure, are omitted here. The protoplanet radius is only 0.001 times its Hill radius, and two zoom insets are shown. From Johansen & Lambrechts (2017, Figure 2), reprinted with permission from AAS.

large asteroids. Subsequent investigations and simulations have confirmed and developed the picture of efficient pebble accretion within a turbulent gas disk.

**Simulations** Many studies of pebble accretion and associated planet formation, under various conditions, have now been made, including • planetesimal formation (e.g. Tanigawa & Ohtsuki, 2010; Perets & Murray-Clay, 2011; Mitra et al., 2013; Wahlberg Jansson & Johansen, 2014; Drazkowska et al., 2016; Hopkins, 2016b; Ida & Guillot, 2016; Krijt et al., 2016; Visser & Ormel, 2016; Wahlberg Jansson et al., 2017; Wahlberg Jansson & Johansen, 2017; Xu et al., 2017d); • embryo and planet growth (e.g. Morbidelli & Nesvorný, 2012; Ormel & Kobayashi, 2012; Johansen & Lambrechts, 2017); • giant planet core formation (e.g. Chambers, 2014; Kretke & Levison, 2014; Lambrechts et al., 2014; Lambrechts & Johansen, 2014; Ali-Dib et al., 2017); •  $\text{H}_2\text{O}$ -delivery to terrestrial embryos (Sato et al., 2016b), • and on various implications for chemical structure and atmospheric chemical abundances (C/O and O/H) as a result of core accretion, core erosion, and migration (e.g. Madhusudhan et al., 2017; Booth et al., 2017b; Chambers, 2017). Further details of the associated ‘inside-out’ planet formation are given below.

**Example results and time scales** In their simulations of core growth from a seed mass by gas-drag-aided capture of cm-sized pebbles, Lambrechts & Johansen (2012) identified two accretion regimes, one set by the azimuthal and radial particle drift for the lower seed masses (in which the optimally-accreted particle size increases with core mass) and the other, for higher masses, by the velocity at the edge of the Hill sphere (for which the optimal size is of order cm, independent of core mass). They concluded that pebble accretion can explain rapid gas and ice giant formation in the core accretion scenario (Figure 10.13), even at wide stellar separations (Figure 10.14). Fig-

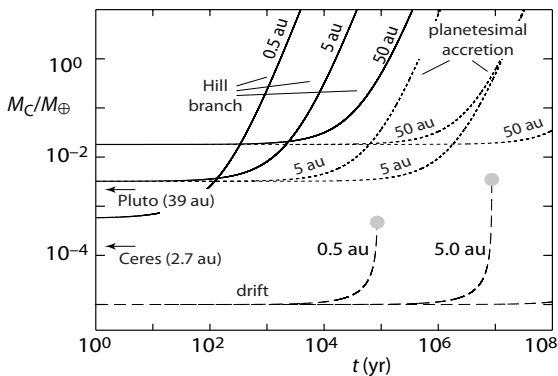


Figure 10.13: Core growth as a function of time, over 0.5–50 au. The drift branch (long-dashed lines) assumes an initial core mass  $M_0 = 10^{-5} M_\oplus$ . Drift growth continues until the transition mass (grey circles) is reached, after which accretion continues through the more efficient Hill branch (solid lines), shown (re-)starting from the transition mass at  $t = 0$  (drift accretion at 50 au takes  $> 10^8$  yr, and its transition mass is not plotted). Dotted curves are classical planetesimal accretion: the faster growth corresponds to 2d accretion of planetesimal fragments (Rafikov, 2004), and the slower to 3d planetesimal accretion (e.g. Dodson-Robinson et al., 2009). From Lambrechts & Johansen (2012, Figure 11), reproduced with permission © ESO.

ure 10.14 contrasts the rapid core growth by pebble accretion in the Hill regime, with the significant longer core formation times for planetesimal accretion in which solids cannot be accreted from the entire Hill sphere.

Compared to the gravitationally-focused accretion of low-scale-height planetesimal fragments, or standard km-sized planetesimals, Lambrechts & Johansen (2012) found that the core growth time scale is shortened by a factor 30–1000 at 5 au, and by a factor 100–10 000 at 50 au, apparently resolving the long-standing core accretion time-scale conflict. Growth in the outer disk remains efficient out to  $\sim 100$  au, with pebble growth sufficiently fast to overcome catastrophic migration of the cores (Lambrechts & Johansen, 2014).

Simulations of the (slowest) oligarchic growth phase of giant planet cores incorporating pebble accretion are described by Chambers (2014). These include (i) planetesimal fragmentation due to mutual collisions, rapidly generating a population of pebbles, (ii) modified capture rate of planetesimals due to a core’s atmosphere, (iii) drag with the disk gas during encounters with the core (or pebble accretion), (iv) modification of particle velocities by turbulence and drift caused by gas drag, (v) the presence of a population of mm-to-m size pebbles that represent the transition point between disruptive collisions between larger particles, and mergers between dust grains, and (vi) radial drift of small objects due to gas drag. For an initial solid surface density of  $120 \text{ kg m}^{-2}$  at 5 au, with 0.1-m diameter pebbles and a disk viscosity parameter  $\alpha = 10^{-4}$ , a  $10 M_\oplus$  core can form in 3 My for 1–10 km diameter planetesimals.

In their simulations of embryo interactions, Chrenko et al. (2017) showed that pebble accretion alters the orbital evolution of embryos undergoing type-I migration, with eccentricities naturally excited ( $e \sim 0.03$ ) due to the presence of an asymmetric under-dense lobe of gas, or *hot trail*, produced by accretion heating of the embryo’s vicinity. Eccentric orbits lead the embryos to frequent close encounters and make resonant locking more difficult. This ‘overly efficient’ type I migration

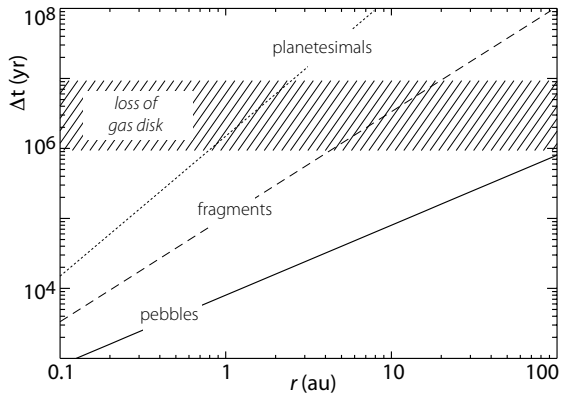


Figure 10.14: Time needed for core growth to  $10 M_\oplus$  at various disk locations. The solid black line gives the core formation time for pebble accretion in the Hill regime, while others give the time needed to form the critical  $10 M_\oplus$  core by planetesimal accretion. The long-dashed line represents planetesimal fragmentation accretion from a thin mid-plane layer (Rafikov, 2004). The shaded area shows the time interval in which the protoplanetary disk loses its gas, encompassing the estimated age of the gas giant LkCa 15 b (Kraus & Ireland, 2012). Core formation needs to occur before this time. From Lambrechts & Johansen (2012, Figure 12), reproduced with permission © ESO.

leads to difficulties in reproducing observed system properties, such as planetary mass, semi-major axis, and eccentricity distributions, while at the same time generating a wide range of bulk densities, as well as plentiful ‘free-floating’ ejected planets (Brasser et al., 2017; Matsumura et al., 2017).

The pebble accretion rate depends on disk conditions such as the disk heating source (viscous heating or stellar irradiation), drag law (Stokes or Epstein, and weak or strong coupling), and in the 2d (larger embryos or in inner regions, corresponding to an infinitely thin disk) or 3d (smaller embryos or outer disk regions) accretion modes, as well as on the sublimation and destruction of icy pebbles inside the snow line. Preferential pebble formation may accompany the preferential recondensation of  $\text{H}_2\text{O}$ -ice during the low-cooling rates following FU Ori-type outbursts (Hubbard, 2017a,b).

Although simulations show that pebble accretion can produce a large diversity of systems, robust conclusions require detailed prescriptions of disk evolution and pebble growth, sublimation, destruction and migration (Ida et al., 2016; Chambers, 2016). Arguments supporting pebble accretion models for solar system objects are given in the box, page 473. Specific laboratory collision experiments, to investigate the collisional fate of pebbles during gravitational collapse, were undertaken by Bukhari Syed et al. (2017).

**Multi-planet systems invoking pebble accretion** The compact multi-transiting systems discovered by Kepler, and in particular the ‘systems with tightly-packed inner planets’ (§6.30.3), typically with several planets of (super-)Earth mass on aligned, sub-au orbits, currently represent a particular challenge for formation theories. Explanations fall into two broad classes (§10.7.3): formation further out in the disk (where solids are more abundant) followed by inward migration, or formation

**Pebble accretion in the solar system:** Based on the pebble accretion model, Wahlberg Jansson & Johansen (2014) predicted that the Rosetta mission would find that comet 67P/Churyumov–Gerasimenko is a ‘pebble-pile planetesimal’ comprising primordial pebbles. This has been confirmed by data from the Philae landing in 2014 November (Fulle et al., 2016; Poulet et al., 2016; Barucci & Fulchignoni, 2017). Specifically, Blum et al. (2017) concluded that the comet likely formed through the gentle gravitational collapse of a bound clump of mm-sized dust aggregates (pebbles), intermixed with microscopic ice particles.

This formation scenario leads to a cometary make-up that is compatible with the porosity, homogeneity, tensile strength, thermal inertia, vertical temperature profiles, sizes and porosities of emitted dust, and the steep increase in H<sub>2</sub>O-vapour production with decreasing heliocentric distance, measured by both Rosetta and Philae. In turn, the findings suggest that the pebbles observed to be abundant in protoplanetary disks around young stars provide the building material for comets and other minor bodies.

Pebble formation has also been invoked as one formation scenario for the inferred Planet Nine (Kenyon & Bromley, 2016a, see also §12.5.8), and for the formation of the Galilean satellites, in particular replicating their H<sub>2</sub>O content (Ronnet et al., 2017).

*in situ*, in the inner regions of the disk, perhaps in disks with surface density profiles similar to the minimum-mass solar nebula, but enhanced by factors  $\geq 10$ .

**Inside-out planet formation** An alternative, invoking pebble accretion, is that planets are formed sequentially in the inner disk, from the inside-out, through successive gravitationally-unstable rings fed from a stream of (cm- to m-size) pebbles delivery to the mid-plane, and drifting inward via gas drag (Chatterjee & Tan, 2014). Pebbles collect at the pressure maximum associated with the transition from a dead zone to an inner magnetorotational instability zone (Figure 10.6).

Pebbles trapped by the pressure maximum build up in a ring, either becoming gravitationally unstable to form a  $\sim 1M_{\oplus}$  planet directly, or through continued accretion growth. This may also involve various processes, including streaming instabilities, gravitational instabilities, and/or Rossby wave instabilities. The protoplanet grows until it becomes massive enough to open a gap in the disk. This gap pushes the pressure maximum outward by a few Hill radii, thus creating a new pebble trap that is displaced from the planet’s orbit. Alternatively, the planet may undergo type I migration into the active region, allowing a new ring and planet to form behind it.

A variety of densities may result depending on the importance of residual gas accretion as the planet approaches its isolation mass. The process can repeat with a new pebble ring gathering at the pressure maximum associated with the retreating dead-zone boundary. Detailed models of this *inside-out planet formation* yield planet masses, mass scalings with orbital radius, and minimum orbital separations consistent with those seen by Kepler (Boley et al., 2014; Chatterjee & Tan, 2014, 2015; Moriarty & Fischer, 2015; Hu et al., 2016; Tan et al., 2016; Guilera & Sándor, 2017; Ali-Dib & Lakhiani, 2018; Hu et al., 2018).

Chatterjee & Tan (2015) used the model to determine the mass of the resulting innermost ‘Vulcan’ planet,  $M_{p,1}$  inferring  $M_{p,1} \sim 5.0[r/(0.1 \text{ au})]$ , a dependency reasonably consistent with the observed Kepler innermost ‘Vulcans’  $M_{p,1} \propto r^{0.7 \pm 0.2}$ .

Hu et al. (2018) estimated that compact systems can form, on time scales comparable to disk lifetimes, for disk accretion rates of  $\sim 10^{-9} M_{\odot} \text{ yr}^{-1}$  and with relatively low viscosity in the dead zone inner boundary region,  $\alpha \sim 10^{-4}$ .

**Formation at the snow line** A different model based on pebble accretion has been suggested for the formation of TRAPPIST-1, and by extrapolation to other compact systems including those with a number of close-in super-Earths (Ormel et al., 2017). In this scenario, planet formation starts at the H<sub>2</sub>O-ice line, where pebbles originating in the outer disk accumulate to trigger streaming instabilities. After their formation, planetary embryos quickly mature by pebble accretion.

Planet growth stalls at Earth masses, where the planet’s gravitational feedback on the disk repels pebbles. Planets are then transported by type I migration to the inner disk, where they stall at the magnetospheric cavity, and end up in mean motion resonances. During disk dispersal, the cavity radius expands and the innermost planets escape resonance. One prediction of the model is that few close-in compact systems would harbour giant planets at large distances, since they would have inhibited the pebble flux from the outer disk.

#### 10.4.5 Planetesimal coagulation

Studies of the coagulation stage of planet formation aim to explain the properties of bodies that ultimately form, such as their number, size distribution, formation time scale, and the mass fraction in the original planetesimals that ends up in big bodies. Coagulation is usually studied with numerical simulations. Starting from an assumed initial state, the planetesimals begin to merge. The merging rate depends on gravitational focusing factors, which are functions of the relative speeds. The relative speeds are in turn affected by a variety of two-body processes such as inelastic collisions, viscous stirring, and dynamical friction.<sup>3</sup>

There have been many such simulations, using a variety of techniques (e.g. Greenberg et al., 1978; Wetherill & Stewart, 1989; Kokubo & Ida, 1998; Weidenschilling et al., 1997; Kenyon & Luu, 1999; Inaba et al., 2001; Morbidelli et al., 2009a; Ormel et al., 2010b; Weidenschilling, 2011; Schlichting & Sari, 2011), including those with an emphasis on the solar system (Goldreich et al., 2004b).

However, the simulations are complicated, not always in agreement, and it can be difficult to disentangle the various effects and draw general conclusions.

<sup>3</sup> *Viscous stirring* is a result of equipartition of energy between large and small gravitationally-interacting bodies, in which (for example) the orbital energy of a large passing body is transferred into the kinetic energy of other smaller particles. *Dynamical friction* is a force exerted by small objects that damps the random motions of large objects. It occurs via gravitational focusing of small bodies behind the orbit of the large body. Dynamical friction from planetesimals acting on planetary embryos keeps the eccentricities and inclinations of the embryos relatively small, such that collisions between embryos only occur once the planetesimal population is largely depleted.

Compounding the difficulty are a number of uncertainties, such as the unknown initial size and velocity distributions, details of collisional fragmentation, and when gaps are opened in the circumstellar disk.

Early coagulation simulations led to the discovery of runaway growth, in which the size distribution quickly develops a tail extending to extremely large sizes (Safronov, 1972; Greenberg et al., 1978; Wetherill & Stewart, 1989).

The present picture is that of a runaway growth phase, followed by periods of self-regulated oligarchic growth, and post-oligarchic chaotic growth.

**Runaway growth: 10 km to 100 km** Mutual gravitational interactions between planetesimals become more important as their mass increases, since their effective collisional cross section is much larger than their physical cross section. As a result, object deflection, or *gravitational focusing*, starts to have a significant effect on collisional probabilities (Greenzweig & Lissauer, 1990; Armitage, 2007a, eqn 151–155). At the same time, dynamical friction develops as an important mechanism for transferring kinetic energy from larger to smaller planetesimals (Stewart & Wetherill, 1988), keeping the velocity dispersion of the most massive bodies relatively low, and reducing the formation time scale.

Neglecting the embryo's effect on growth of the velocity dispersion in the disk, and assuming gravitational focusing is strong, then (Wetherill & Stewart, 1989; Rafikov, 2003b,a, eqn 4)

$$\frac{1}{M_e} \frac{dM_e}{dt} \propto M_e^{1/3}, \quad (10.17)$$

and the embryo growth accelerates as its mass increases. This corresponds to a phase of *runaway growth* (Stewart & Wetherill, 1988; Wetherill & Stewart, 1989), in which a few bodies grow rapidly at the expense of others. Runaway growth leads to the formation of  $\geq 100$  km-sized bodies at 1 au in some  $10^4$  yr, the process having been studied both analytically and through N-body simulations (Kokubo & Ida, 1996; Weidenschilling et al., 1997; Lee, 2000; Malyshev & Goodman, 2001; Rafikov, 2003a).

Detailed modeling must consider whether collisions lead to accretion growth, or to fragmentation. Colliding bodies may (i) bounce off each other elastically and remain unbound, (ii) dissipate sufficient kinetic energy to become gravitationally bound, with or without fragmentation, or (iii) disrupt or shatter one or both bodies, creating a number of unbound fragments. The overall outcome is determined by mass, impact velocity, and less certain parameters such as intrinsic strength (Benz & Asphaug, 1999; Leinhardt & Richardson, 2002; Ryan & Melosh, 1998; Barnes et al., 2009d; Ormel et al., 2010b,a; Schlichting & Sari, 2011; Kobayashi et al., 2016).

With the progressive formation of massive planets changing the velocity distribution through gravitational

interactions, conditions are believed to develop from those more favourable for accretion into those more favourable for disruption (e.g. Ormel et al., 2010a). In the solar system, constraints come from collisional processes inferred in the evolution of the Kuiper belt (Stern & Colwell, 1997a,b), and from present-day collisions in the asteroid belt where impact velocities can be large (Bottke et al., 1994), leading to the fragmentation and formation of asteroid families (Nesvorný et al., 2002).

A consideration of three-body *shear dominated* dynamics, affected by the gravitational influence of the star, leads to a reduction in collisional rate compared with the expectations from two-body *dispersion dominated* dynamics (Rafikov, 2003a; Goldreich et al., 2004b).

Various theories have been proposed to explain how runaway growth ends, the resulting size spectrum of the large bodies, and the processes that follow (e.g. Ida & Makino, 1993; Kokubo & Ida, 1998; Goldreich et al., 2004b; Ormel et al., 2010b; Schlichting & Sari, 2011).

**Trans-Hill stage** Lithwick (2014) has suggested that runaway growth ends with a *trans-Hill stage*, in which the big bodies that dominate the viscous stirring reach a Hill velocity matching the random speed of the small bodies that they accrete. During trans-Hill growth, conglomeration can be categorised as collisionless, in which the smaller bodies rarely collide, or collisional, in which the small bodies' dispersion is reduced by frequent inelastic collisions (Weidenschilling, 2011; Shannon et al., 2015b), with very different outcomes for formation efficiency and size spectrum.

The trans-Hill growth stage determines the growth efficiency of the larger bodies, as well as their growth time scale and size spectrum, and can terminate in one of two ways, depending on the sizes of the small bodies. Either mutual accretion of big bodies can become significant and growth proceeds until half the total mass is converted into big bodies, which may explain the observed size distributions of small bodies in the solar system. Alternatively, if the orbits of the big bodies become separated by their Hill radius, oligarchic growth, leading to the formation of fully-fledged planets, commences.

Further studies suggest that the resulting size spectrum,  $dn/dR \propto R^{-4}$ , and low formation efficiency at the relevant radial distance present problems for previous models of the formation of the Kuiper belt and extrasolar debris disks, and may point to the need for direct gravitational collapse or strong collisional cooling of small planetesimals (Shannon et al., 2015b).

**Oligarchic growth: 100 km to 1000 km** The size of a growing planet's *feeding zone* is set by the maximum distance over which its gravity is able to perturb other orbits sufficiently to allow collisions. The feeding zone itself scales with the Hill radius, the radius within which the gravity of the planet dominates that of other bodies within the system (box, page 512). As the mass of

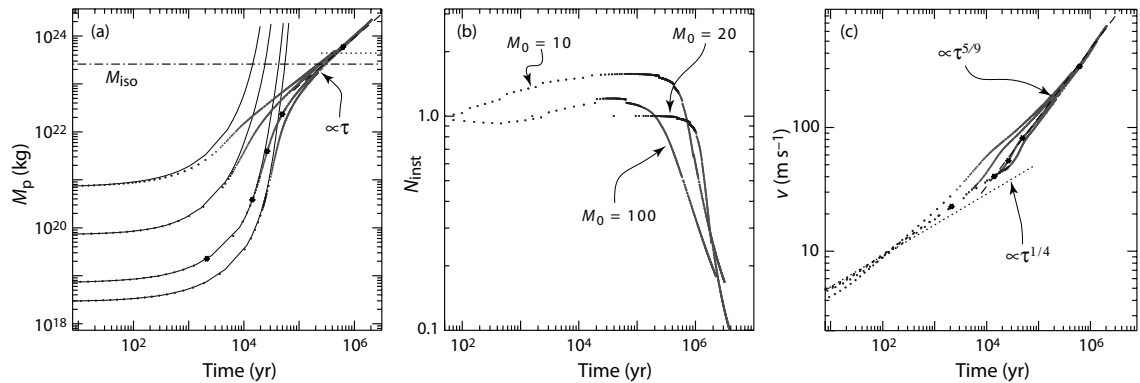


Figure 10.15: Simulated growth of objects in a planetesimal disk: (a) embryo mass as a function of time (solid or dashed lines) for  $a = 0.9$  au and  $m = 7.9 \times 10^{17}$  kg, for different initial conditions. Thin solid lines indicate runaway curves obtained by neglecting the embryo's dynamical effects. The dot-dashed line is the isolation mass. The  $M_p \propto \tau$  line shows the asymptotic behaviour; (b) instantaneous surface density of planetesimals which can be accreted by the embryo  $N_{\text{inst}}$  as a function of time, for three different values of (dimensionless) initial embryo mass,  $M_0$ . There is a sharp drop of  $N_{\text{inst}}$  after the embryos start to dominate the disk dynamics; (c) growth of the planetesimal velocity dispersion as a function of time, for different initial conditions. The dotted line with slope  $1/4$  shows the initial growth due to planetesimal-planetesimal scattering alone. The dashed line with slope  $5/9$  is the asymptotic behaviour. From Rafikov (2003a, Figures 7, 10, 11), by permission of IOP Publishing/AAS.

the largest planetesimals grow, they perturb the velocities of smaller planetesimals in their vicinity, reducing the number on roughly circular orbits which are available for accretion. In other words, at some point, the runaway body dynamically heats its environment, gravitational focusing factors decrease, and runaway growth passes into oligarchic growth.

This leads to a slowdown in the accretion rate once a certain *isolation mass* is reached, and runaway growth gives way to a phase of slower *oligarchic growth*. The largest objects still grow at the expense of smaller bodies, but more slowly, and all roughly at the same rate.

This slowdown occurs because, although the feeding zone expands as the planet mass grows, the number and mass of available planetesimals in the enlarged feeding zone rises more slowly than linearly. Armitage (2007a, eqn 172–177) gives for the isolation mass

$$M_{\text{iso}} \propto M_{\star}^{-1/2} \Sigma_{\text{p}}^{3/2} r^3, \quad (10.18)$$

where  $\Sigma_{\text{p}}$  is the surface density of planetesimals at radial distance  $r$ . For  $\Sigma_{\text{p}} = 100 \text{ kg m}^{-2}$ , conditions in the terrestrial planet region (Lissauer, 1993) and gas giant core regimes (Pollack et al., 1996) suggest isolation masses of  $\sim 0.07 M_{\oplus}$  and  $9 M_{\oplus}$  respectively. The latter is comparable to the estimated Jovian core mass (Guillot, 2005).

Simulation results differ in detail, and do not necessarily display distinct sequences of orderly growth, runaway growth, and oligarchic growth (e.g. Rafikov, 2003a). Some illustrative results are shown in Figure 10.15. Destructive processes include evaporation as a result of bow shocks associated with planetesimals orbiting with supersonic velocities relative to the gas in a protoplanetary disk (Tanaka et al., 2013). Typically, runaway growth

may occur after  $\sim 10^5$  yr when the relative velocities of the larger bodies temporarily fall into a low-velocity regime. After  $\sim 10^6$  yr, results point to a number of relatively isolated protoplanets (or planetary embryos) distributed throughout the disk.

Conceptually, the resulting picture is of some 100 objects around 1000 km in size, with masses of  $10^{22} - 10^{23}$  kg (Moon- to Mars-sized), accompanied by a swarm of billions of 1–10 km planetesimals (Kokubo & Ida, 1998, 2000, 2002; Rafikov, 2003a; Thommes et al., 2003; Fogg & Nelson, 2005; Chambers, 2006b; Cresswell & Nelson, 2006; Kenyon & Bromley, 2006; Ford & Chiang, 2007; Fortier et al., 2007; Ogihara et al., 2007; Zhou et al., 2007; Brunini & Benvenuto, 2008; Chambers, 2008; Fortier et al., 2009; Mann et al., 2010; Ormel et al., 2010a; Coleman & Nelson, 2014; Kenyon & Bromley, 2014a; Alibert, 2017; Morishima, 2017).

**Post-oligarchic growth: 1000 km to 10 000 km** When the mass in relatively isolated protoplanets, or oligarchs, is roughly comparable to the mass in planetesimals, strong dynamical interactions lead to a more chaotic collision phase and merger rate. Orbits of neighbouring embryos begin to cross, and their eccentricities and inclinations increase rapidly. Gravitational focusing weakens, and the growth rate drops significantly.

This *post-oligarchic* or *chaotic growth phase* is characterised by large-scale, stochastic mixing of the planetary embryos and catastrophic collisions, leading to the formation of several terrestrial planets, and ultimately defining the final architecture of the planetary system. The growing protoplanetary embryos, above  $\sim 3000$  km in size, are also accompanied by their internal melt-

ing and progressively differentiated interiors, as a result of radiogenic, gravitational, or impact heating (§10.4.7). Protoplanet atmospheres further affect the dynamics and tidal torques (Terquem & Heinemann, 2011).

Mergers proceed until orbit spacings become large enough to be quasi-stable, with the final assembly of terrestrial planets taking  $\sim 10$ – $100$  Myr (Chambers & Wetherill, 1998; Goldreich et al., 2004a; Moorhead & Adams, 2005; Kokubo et al., 2006; Kenyon & Bromley, 2006; Ogiwara & Ida, 2009; Ronco et al., 2015; Tremaine, 2015; Haghighipour & Winter, 2016). Water delivery to planets in the habitable zone is also determined during this phase (e.g. Hansen, 2015; Ronco et al., 2015).

During this stage, collisional fragmentation is not a barrier to rocky planet formation even at small distances from the host star of some 1.1 Roche radii, with tidal effects causing excessively fragmenting collisions within that distance (Wallace et al., 2017).

**Example simulations** Monte Carlo simulations by Hansen & Murray (2013) and Hansen (2015) have been run to examine the extent to which the post-oligarchic assembly phase can reproduce the extensive Kepler observations of low-mass ( $M_{\text{tot}} < 25M_{\oplus}$ ) planetary systems around G dwarfs and M dwarfs respectively, by invoking *in situ* gravitational assembly of planetary embryos into final planets. Integrations began at the end of the oligarchic assembly phase, using the equations of Kokubo & Ida (1998) to specify the distribution of the initial planetary embryos in mass and semi-major axis.

For G dwarfs, the benchmark disk is the minimum-mass solar nebula (§10.3), although current observations suggest substantially more mass than in the solar system (e.g. Hansen & Murray, 2012, 2013; Chiang & Laughlin, 2013). For M dwarfs, Hansen (2015) invoked a scaled-down surface density profile  $\Sigma = M_p/2\pi a_p \Delta a_p$ , derived from the observed distribution of  $R_p$  and  $a_p$  for transiting planets around M dwarfs from Kepler, along with a prescription to estimate  $M_p$  from the observed  $R_p$ , e.g.  $M_p = (R_p/R_{\oplus})^{2.06}$  (Lissauer et al., 2011b).

Based on a protoplanetary disk of  $20M_{\oplus}$  around a  $1M_{\odot}$  star, and assuming a power-law surface density distribution that falls with distance  $a$  as  $\propto a^{-1.5}$ , Hansen & Murray (2013) derived simulated distributions of  $M_p$ ,  $e$ ,  $i$ , and  $\Delta P$ . They found a broad agreement in terms of the relative frequencies of multi-planet systems, the distribution of  $\Delta i$  (at least when moderate tidal circularisation is taken into account), and the broad features of the distributions in  $P$  and  $R_p$ . The most striking disagreement was in the ratio of single to multi-planet systems, with 50% more single planets observed than are produced in any model. This feature is detailed further in Section 6.30.6.

Hansen (2015) carried out similar simulations for lower mass ( $0.5M_{\odot}$ ) M dwarfs. They found broad agreement with the observed sample of cool Kepler planet candidates from Dressing & Charbonneau (2013), reproducing the observed distribution of planetary periods and period ratios, although again finding an underabundance of single transit systems. Almost every simulated system contained at least one planet in the habitable zone, with volatile delivery potentially producing a  $\text{H}_2\text{O}$  content comparable to that of Earth.

**Algorithmic implementation** Numerical studies of the various stages of terrestrial planet formation require N-body algorithms combined with those handling various processes rele-

vant at different stages. Amongst published simulations, those made available include: SOLARIS, which follows the early and later phases and includes gravitational forces, aerodynamic drag, and type I and type II migration (Süli, 2013); Orchestra, which uses a coagulation code to treat the growth of planetesimals into oligarchs, and explicit N-body calculations to follow the evolution of oligarchs into planets (Bromley & Kenyon, 2006, 2011b, 2013). PENTACLE, a parallelised particle–particle particle-tree code, based on a hybrid N-body integrator, and handling 1–10 million particles in a high-resolution simulation of collisional dynamics (Iwasawa et al., 2017).

**Giant impacts** Post-oligarchic growth is accompanied by the *giant impact stage*, with collisions occurring analogous to the Moon-forming impact (§12.3.3), and which can take various forms depending on impact geometry, material strength, and equation of state (e.g. Chambers, 2001; Morishima et al., 2010). These are being studied with progressively more refined smoothed particle hydrodynamics (SPH) code (Reinhardt & Stadel, 2017; Emshuber et al., 2018; Golabek et al., 2018).

Head-on collisions may lead to mergers with little mass loss, with large impacts causing extensive heating and the formation of magma oceans (Tonks & Melosh, 1992). Oblique ‘hit-and-run’ collisions may separate and escape, with some exchange of material or atmospheric stripping (Agnor & Asphaug, 2004; Kokubo & Genda, 2010; Genda et al., 2012; Quintana et al., 2016). Collisions may also reduce the envelope-to-core mass ratio by a factor of two, leading to an increase in the observed mean density by factors 2–3 (Inamdar & Schlichting, 2016). Giant impacts may also lead to a connection between orbital properties (for example, in the eccentricities, mutual inclinations, and orbit spacings of super-Earths) and interior/envelope composition (Dawson et al., 2016; Matsumoto & Kokubo, 2017).

Potentially observable consequences are considered further in Section 10.6.4.

**Solar system giant impacts** Earth and Venus each perhaps experienced some 10 giant impacts with other embryos during this phase. Mercury’s high density may indicate that it lost much of its mantle during one or more impacts with another embryo (Benz et al., 1988, 2007; Lykawka & Ito, 2017; Jackson et al., 2018), a hypothesis for which the MESSENGER mission (orbiting Mercury between 2011–15) provided constraints from its inferred thermal history (e.g. Peplowski et al., 2011).

#### 10.4.6 Final configuration

The final size and spacing of terrestrial planets depends on numerous factors, amongst them the initial conditions (Chambers, 2001; O’Brien et al., 2006), the (unknown) viscosity of the protoplanetary disk (Lin & Papaloizou, 1979), the surface density of planetesimals (Raymond et al., 2005b; Kenyon & Bromley, 2006), and the existence and migration of giant planets (Levison & Agnor, 2003). In the solar system, for example, simulations show that the oligarchic and post-oligarchic



growth stages are strongly influenced by the presence of the gas giants, Jupiter and Saturn.

Current theories of planetary growth do not yield deterministic ‘Titius–Bode law’ formulae for planetary orbits (box, page 510), but characteristic spacings do exist, suggesting that gaps develop broadly in proportion to orbital radius (Hayes & Tremaine, 1998; Laskar, 2000).

Applied to the solar system, numerical simulations suggest that the Earth reached half its current mass in 10–30 Myr, and its present mass in ~100 Myr, with the growth rate declining exponentially with time (Chambers, 2001; Raymond et al., 2005b; O’Brien et al., 2006). Such estimates are consistent with those derived from radiometric data, and from cratering records (Grieve & Pesonen, 1996; Stothers, 1998).

The protracted duration of the final stage of accretion implies considerable radial mixing, with material acquired from different regions of the inner disk. This may explain the slightly different oxygen isotope ratios found on Earth and Mars (Clayton & Mayeda, 1996).

In their simulations of terrestrial planet formation, Hoffmann et al. (2017) have shown that practically identical initial conditions can result in a wide range of final planetary configurations. This is a result of the chaotic evolution of trajectories which are highly sensitive to even minor displacements, implying that individual simulations lack detailed predictive power. However, some key global properties still emerge. For example, systems with giant planets tend to form fewer, more massive, and more eccentric terrestrial planets at smaller semi-major axes than those without, while configurations with giant planets on eccentric orbits produce fewer and more massive terrestrial planets on tighter orbits than those with giants on circular orbits.

Another recurrent feature in solar system-like simulations is the existence of ‘sweeping secular resonances’ which move inwards as the gas disk dissipates, exciting the eccentricities and inclinations of small bodies, and carrying embryos and planetesimals inwards. These are described further in Section 12.6.1.

**By-products of planetesimal formation** In the solar system, non-agglomerated planetesimals in the form of asteroids, trans-Neptunian objects and comets provide a detailed record of the physical conditions in the solar nebula, and its subsequent evolution (Chapter 12).

Small remnant bodies are also subject to further scattering by planets, such as in the scattering of comets from the Kuiper belt into the inner solar system (Bonsor & Wyatt, 2012; Raymond & Armitage, 2013). Bonsor & Wyatt (2012) assumed that multi-planet scattering can be considered as a series of three-body problems and derived, for example, the range of particle inclinations (and hence the disc height) at different distances. For certain planetary systems, comets can be scattered from an outer belt, or an Oort cloud analogue, on to star-

grazing orbits, supporting a planetary origin for the dust disks and metal pollution found in various nearby white dwarfs (§8.9.3–8.9.4).

Debris from planetesimal collisions around other stars is a further indication that planetesimal formation, and hence planet formation, is ubiquitous. These ‘debris disks’ are considered further in Section 10.6.

The aftermaths of giant impact events are expected to be observable photometrically (§10.6.4), with atmospheres of post-impact terrestrial planets possibly recognisable as such spectroscopically (§11.4.5).

**Spin rates and obliquities** Planetary rotations and obliquities originate from the accretion of angular momentum during their formation, are affected by late-stage giant impacts, and can be subsequently modified by tidal evolution. Most constraints on final planetary rotation, spin rates and obliquities come from observations of the solar system planets, and the state of knowledge inferred from exoplanet systems is summarised there, both for spin rates (§12.4.5) and obliquities (§12.4.6).

**Crustal stripping during accretion** In the solar system, geochemical studies of planetary accretion and evolution have invoked various degrees of collisional erosion to explain differences in bulk composition between planets and chondrites. Crusts are expected to contain a significant fraction of planetary budgets of incompatible elements, which include the major heat producing nuclides, and crust is preferentially lost relative to the mantle during impacts. Carter et al. (2018) made a dynamical evaluation of *crustal stripping* during accretion, developing a scaling law that approximates the mass of crust that remains in the largest remnant. Using this scaling law, and N-body simulations of terrestrial planet formation, they estimated that some one third of the initial crust is stripped from embryos as they accrete, leading to a reduction of 20% in the budgets of the heat producing elements if the stripped crust does not re-accrete.

#### 10.4.7 Size, shape, and internal structure

As bodies grow progressively in size, there is a developing influence of gravity on their overall shape, and on their internal structure. The relevant effects have been outlined by Basri & Brown (2006), and are illustrated schematically in Figure 10.16, with some solar system examples in Figure 10.17.

**Rocks to planetesimals** The bulk volume of small and intermediate sized rocks is determined by (atomic and molecular) bound electron degeneracy pressure, and gravity plays no role in their size or shape. As mass increases, gravity reaches the level necessary to hold together a rock or rubble pile. This depends on density and

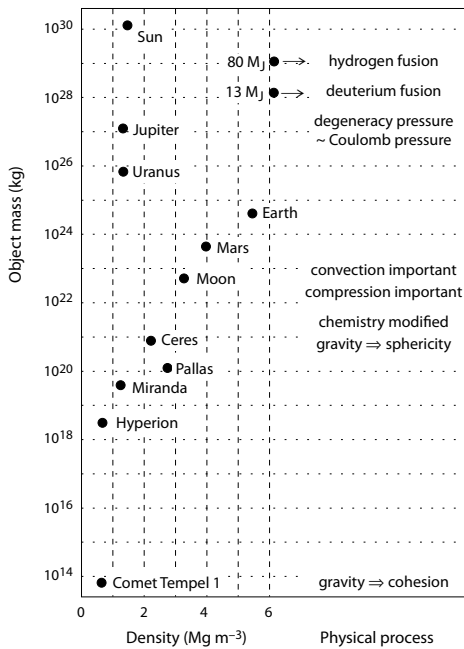


Figure 10.16: The effect of gravity on shape and structure as a function of mass. Some solar system objects are given as examples. The radii of brown dwarfs are approximately constant above  $\sim 13M_J$ , and their densities lie off the plot to the right.

rotation, but starts to operate for small asteroids, as well as comets such as Shoemaker–Levy 9 (which impacted Jupiter in 1994), and Tempel 1 (imaged by Deep Impact in 2005), both with  $D \sim 5$  km and  $M \sim 8 \times 10^{13}$  kg.

Compaction of initially porous material prior to melting influences the interior structure and the thermal evolution of planetesimals in their early history. Specifically, it decreases the porosity resulting in a reduction in radius, and results in an increase in thermal conductivity and thus in a more efficient cooling (Neumann et al., 2014).

At  $D \sim 500 - 1000$  km, gravity overcomes an object's material strength, forcing it (in the absence of rotation) to take the equipotential figure of a sphere. With a dependence on mass and density, solar system objects become gravitationally relaxed, and spherical, at around the size and mass of Ceres ( $D = 940$  km,  $M = 9.4 \times 10^{20}$  kg,  $\rho = 2.1$  Mg m $^{-3}$ ; Thomas et al., 2005), while the smaller asteroids Pallas (608 km) and Vesta (538 km) are slightly elongated in HST images (e.g. McFadden et al., 2007). The largest known substantially non-spherical ice body is Saturn's satellite Hyperion ( $D \sim 100 - 180$  km,  $M = 0.6 \times 10^{19}$  kg,  $\rho = 0.6$  Mg m $^{-3}$ ).

**Planetesimals to planets** The mass threshold for an object to develop a solid-state convective interior, and hence to behave as a fluid over geological time scales, depends on the Rayleigh number in the interior (Turcotte & Schubert, 2002). Scaling as  $D^5$ , solid-state con-

vection becomes important somewhere between the size or mass of the Moon ( $D \sim 3500$  km,  $M \sim 7 \times 10^{22}$  kg) and that of Mars ( $D \sim 6500$  km,  $M \sim 6 \times 10^{23}$  kg).

At a similar mass ( $D \sim 3000$  km for a terrestrial body) the gravitational energy per atom exceeds 1 eV. This corresponds to the typical energy of chemical reactions, so that self-gravity starts to modify the chemical composition of the initial material.

At  $D \sim 6000$  km for rocky material and  $\sim 1000$  km for ices, the central pressure due to gravity exceeds the *bulk modulus* of the material,  $K = -V\partial P/\partial V$  ( $\sim 100 - 1$  GPa, respectively), and significant compression and density increase occur. For rocky materials, this also corresponds approximately to the mass of Mars.

**Brown dwarfs to stars** The next significant change occurs only at  $\sim 1 - 2M_J$ . For such gas giants, core temperatures are large due to the large pressures, and electrons are freed, resulting in a pressure term due to Fermi exclusion. At  $\sim 2M_J$ , free electron degeneracy pressure in the cores becomes comparable to normal Coulomb pressure, and above  $2 - 5M_J$  an increase in mass leads to an increase in density (i.e. a decrease in radius).

The resulting maximum size, at  $2 - 5M_J$ , is modified if the non-degenerate outer layers are hot, i.e. if the giant planet or brown dwarf is young or irradiated, in which case the object can be somewhat more bloated.

**Differentiation** Gravitational pressure, combined with collisional and radioactive heating, facilitate convection and may lead to melting, enhancing *physical differentiation* as high density materials sink (e.g. Li & Chen, 2012). Thus iron, the most common element forming a dense molten phase, sinks towards planetary interiors, while the less dense materials rise. Meteoritic compositions indicate that differentiation occurred even in some asteroids, and gravitational settling is also inferred for the Sun.

In the case of the Earth, the result is a series of compositionally-distinct layers: a dense Fe-rich core, a less-dense magnesium silicate-rich mantle, a thin crust dominated by lighter silicates (Al, Na, Ca, K), a liquid water hydrosphere, and a gaseous N-rich atmosphere.

*Chemical differentiation* is further modified by reactive affinities, determined by the chemical bonds that the element forms. The geochemical *Goldschmidt classification*, proposed in the 1920s by Victor Goldschmidt, denotes preferred host phases, viz. *lithophile* (literally, 'rock' or 'silicate loving', but also O-loving in practice), *siderophile* ('iron loving'), *chalcophile* ('sulphur loving'), and *atmophile* ('gas loving'), dictated by predominantly ionic, metallic, covalent and van de Waals bonding respectively. Thus iron is the host phase for siderophiles such as Ni, Co, or Au, which therefore tend to concentrate in the Earth's core, while silicates provide the host phase for lithophiles such as K, Na, U and W, which tend to concentrate in the crust.

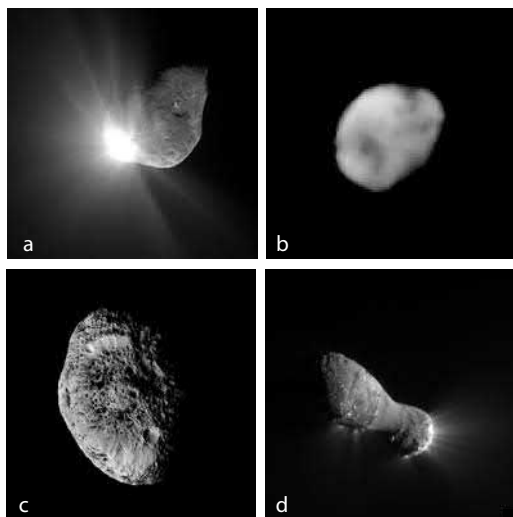


Figure 10.17: Examples of non-spherical low-mass solar system bodies: (a) Comet Tempel 1, 67 s after the collision with the Deep Impact probe in 2005 (NASA); (b) Asteroid Vesta, from HST in 2007 (NASA); (c) Saturn's icy satellite Hyperion, from the Cassini fly-by in 2005 (NASA); (d) Comet Hartley 2 imaged from 700 km by EPOXI in 2010 (NASA/JPL–Caltech/UMD).

The combination of physical and chemical differentiation on Earth results in an average density of  $5.5 \text{ Mg m}^{-3}$ , a mantle density of  $3.4 \text{ Mg m}^{-3}$ , and a crustal density of  $2.7 \text{ Mg m}^{-3}$ . Seismic measurements suggest that the core itself comprises a solid inner core of radius  $\sim 1200 \text{ km}$  and a liquid outer core extending to a radius of  $\sim 3400 \text{ km}$ .

**Exoplanet structures** The wide range of thermal and rotational states attained by terrestrial planets during accretion will be accompanied by a significant range in their physical structure (size, shape, pressure and temperature profile). From their numerical code, HERCULES, which solves for the equilibrium structure as a series of overlapping constant-density spheroids, Lock & Stewart (2017) demonstrated that Earth-like bodies should display a substantial range of morphologies.

Formation models indicate that rocky planets are typically substantially vaporised multiple times during accretion (§10.4.5). Accordingly, they found that a large fraction of post-impact bodies will exceed the corotation limit (when the equatorial rotation intersects the Keplerian orbital velocity). These hot planetary bodies form a structure, which they termed a *synestia* (after the Greek *syn* for connected, and *Hestia* for the goddess of architecture), with a corotating inner region loosely connected to a disk-like (doughnut-shaped) outer region.

The common occurrence of these hot rotating states will influence the physical processes controlling further accretion, core formation and internal evolution, suggests a new mechanism for satellite formation, and expands the mass–radius range for rocky exoplanets.

## 10.5 Giant planet formation

Giant planets play a key role in shaping the architectures of planetary systems. Their large masses, orbital angular momenta, and rapid formation drive complex dynamics, exciting the orbits of smaller bodies, and catalysing the delivery of volatiles to inner terrestrial planets. Their bulk properties probe the physical and chemical conditions of protoplanetary disks from which they formed.

Loosely defined as planets of mass  $\gtrsim 0.1 M_{\text{J}}$  ( $\gtrsim 30 M_{\oplus}$ ; §1.6.2), giant planets span a range of masses, orbits (which may have been modified post-formation), and compositions, and include the solar system gas and ice giants, as well as the extreme close-orbiting hot Jupiters.

Specific processes in the aggregation of protoplanetary disk material, beyond those of terrestrial planet formation, are required to explain their existence: essentially, at small orbital distances the supply of gas and dust required for stable accretion is inadequate, while at very large orbital distances long accretion time scales are problematic.

Their typical substantial gas envelopes provide a strong temporal constraint: they must form rapidly, before the protoplanetary gas disk dissipates, viz. within  $\sim 5\text{--}10 \text{ Myr}$ . Models are also guided by the structure (mass and density), elemental composition, and orbital characteristics of the solar system giants (§12.2.2).

Two formation models for giant models continue to be explored: the (more widely-embraced) *core accretion* model (§10.5.1), and the *disk instability* model (§10.5.2). The former begins, as for the terrestrial planets, with planetesimal coagulation forming a massive core of some  $5\text{--}20 M_{\oplus}$ , followed by the rapid accretion of a gaseous envelope. In the latter, gas giants are held to form as a result of gravitational fragmentation in the protoplanetary disk. Strengths and challenges for each model are summarised in Section 10.5.3.

### 10.5.1 Core accretion

**Overview** Sometimes described as ‘bottom-up’, the core accretion model of giant planet formation starts with the formation of a massive planet core, followed by the core’s rapid accumulation of a massive gas envelope. This process of *classical core accretion* is generally considered as taking place in four main phases, which may be further modified by the effects of migration.

This section gives an overview of these four main phases, with some details inserted to expand on the ‘bigger picture’. Subsequent sections treat key aspects and further complexities in more detail. Various recent reviews give further details (e.g. Weidenschilling, 2005; Hubickyj, 2006; Thommes & Duncan, 2006; Mordasini et al., 2008; Hubickyj, 2010; Helled et al., 2014).

- Phase 1, primary core accretion: this first phase resembles that of terrestrial planet formation described previ-

ously, leading to (and requiring) the formation of a massive planet, or core, of some  $5 - 20M_{\oplus}$ , capable of retaining a gaseous atmosphere. The core accretes planetesimals until it has obtained most of the solid mass within its gravitational reach, and its mass approaches what is termed the *isolation mass*,  $M_{\text{iso}}$ . The *envelope mass*,  $M_{\text{env}}$ , also grows, but it remains only a small fraction of the *core mass*,  $M_{\text{core}}$ .

Simulations indicate that there are generally insufficient solids in the inner disk to allow such massive cores to develop, but the situation is more favourable beyond the snow line (§11.2.3), where the temperature is low enough for the formation of  $\text{H}_2\text{O}$  (and other) ices, substantially augmenting the surface density of condensates. This enhancement in potential accretion material, combined with the reduced gravitational dominance of the central star, allows large solid cores to form more easily.

- **Phase 2, slow envelope accretion:** this is characterised by a slowly increasing accretion of gas onto the core, along with the continued accretion of residual planetesimals. Over a period of a few Myr, the growing core eventually reaches a *critical core mass* (Bodenheimer & Pollack, 1986), also referred to as the *crossover mass* (Pollack et al., 1996), beyond which the gas accretion rate exceeds that of planetesimals by an amount which grows exponentially with time.

$\dot{M}_{\text{core}}$  drops considerably, and  $\dot{M}_{\text{env}}$  increases until it exceeds  $\dot{M}_{\text{core}}$ . As the envelope mass increases, the expanding zone of gravitational influence allows more planetesimals to be accreted, but at a slow, nearly constant rate.  $\dot{M}_{\text{env}}$  is limited by the ability of the envelope to radiate energy and contract, so this rate is also slow, about 2–3 times that of the core. The time scale depends on the envelope opacity and, including grain settling, lies in the range 0.5 to a few Myr.

- **Phase 3, rapid gas accretion:** this is triggered if the envelope reaches a mass comparable to the core mass. It is characterised by runaway accretion of the surrounding gas, with relatively little accretion of solids.

After crossover ( $M_{\text{core}} = M_{\text{env}} \approx \sqrt{2}M_{\text{iso}}$ ), the rate of gas accretion increases continuously, although the structure remains in quasi-hydrostatic equilibrium (e.g. Mizuno, 1980). Envelope growth greatly exceeds that of the core. Eventually the protoplanetary disk cannot supply gas fast enough to keep up with the contraction of the envelope.  $\dot{M}_{\text{env}}$ , instead of being determined by the radiation of energy by the planet, is then determined by the properties of the disk in the vicinity of the planet. Beyond this point, the accretion flow of the gas is hydrodynamic, nearly in free fall, onto a protoplanet which is in hydrostatic equilibrium at a radius much smaller than  $R_{\text{eff}}$ . The core mass remains nearly constant on the time scale of the growth of the envelope. The time scale to build up to  $\sim 1M_J$  is  $10^4 - 10^6$  yr, depending on the assumed disk viscosity.

During this rapid accretion phase, hydrodynamic collapse of the gaseous envelope is avoided if gas is supplied rapidly enough to compensate for an increasingly rapid contraction of the outer envelope, and an increasingly rapid expansion of the planet's growing sphere of gravitational influence.

Once the envelope mass exceeds a few percent of  $M_{\oplus}$ , a combination of gas drag, evaporation, and dynamical pressure makes it increasingly difficult for planetesimals to arrive intact

at the core boundary, and a significant mass fraction dissolves in their gaseous envelopes, enriching them in high- $Z$  elements. Such a scenario broadly accounts for the enhancement of some high- $Z$  elements in the atmospheres of the solar system giants, and for their progressive enrichment from Jupiter to Neptune (Podolak et al., 1988; Simonelli et al., 1989). Planetesimal accretion might be inhibited at certain stages through the protective mechanism of mean motion resonances (Zhou & Lin, 2007), while late-stage dust accretion may be limited to particles of very small size (Paardekooper, 2007).

- **Phase 4, contraction and cooling:** this is marked by the end of gas accretion, either due to the opening of a disk gap (assuming that this is unbridged by accretion streams), or because the gas disk dissipates (e.g. Tanigawa & Ikoma, 2007). The planet then embarks on its indefinite stage of contracting and cooling at constant mass to its present state.

The main energy source is slow contraction in hydrostatic equilibrium, while an energy sink arises from cooling by radiation. If the planet accretes a mass of  $\approx 13M_J$ , deuterium burning may be relevant (Mollière & Mordasini, 2012; Bodenheimer et al., 2013). Once accretion terminates, heating via planetesimal accretion ceases, but for a planet very close to its star, stellar irradiation, tidal dissipation and magnetic dissipation may provide additional energy.

The first three phases are illustrated in Figure 10.18. These three phases can change with the exchange of angular momentum between planet and disk (Baruteau et al., 2014), and when the planet's orbital parameters evolve through migration.

The scenario can explain a wide range of planetary architectures, including the solar system gas and ice giants, and many of the exoplanet giants, at least to those orbiting within  $r \leq 10 - 50$  au.

Cores of adequate mass for large-scale gas accretion only form under certain conditions within the protoplanetary disk. Further, the processes of massive core formation, and gas dispersal with the disk, operate on comparable time scales of order 5–10 Myr. Consequently, if the disk conditions are not suitable for a massive core to form, or the massive core cannot form rapidly enough, the gas disk may be dispersed before it can accrete, and no giants are formed. For smaller core masses, or longer core formation time scales, the residual gas can be dispersed before accretion runs its full course, and ice giants rather than the gas-rich gas giants may result. In consequence, details of individual systems is rather sensitive to initial conditions.

**Model developments** Early ideas were set out to explain the formation of the solar system giants planets, and subsequently developed further with the discovery of giant exoplanets (e.g. Mizuno et al., 1978; Mizuno, 1980; Stevenson, 1982a; Pollack, 1984; Bodenheimer & Pollack, 1986; Pollack et al., 1986; Podolak et al., 1988; Pollack et al., 1996; Papaloizou & Terquem, 1999; Kokubo & Ida, 2000; Bodenheimer et al., 2000).

Early models faced various difficulties, amongst them the long time scales required for planetary accretion far out in the disk (Lissauer, 1987); the possibility of dynamical instabilities leading to ejection of the gaseous envelope (Wuchterl, 1990, 1991a,b); and reproducing the detailed low- and high- $Z$  abundances of Uranus and Neptune, and their partitioning between core and envelope (Pollack et al., 1996).

**Core growth** Core accretion simulations start with an embryo of  $0.01 - 0.1M_{\oplus}$  accreting planetesimals spanning a range of sizes. The accretion rate is approximated by the Safronov equation (Safronov, 1969)

$$\dot{M}_{\text{core}} = \pi R_{\text{capt}}^2 \sigma_s \Omega F_g, \quad (10.19)$$

where  $\pi R_{\text{capt}}^2$  is the geometrical capture cross section,  $\Omega$  is the orbital frequency,  $\sigma_s$  is the solid surface density of the disk, and  $F_g$  is a *gravitational enhancement factor*. If no gas is present, then  $R_{\text{capt}} = R_{\text{core}}$ . In the presence of an envelope, gas drag and ablation can result in planetesimal deposition outside the core, with  $R_{\text{capt}} > R_{\text{core}}$ .

In the two-body approximation in which the effect of the host star is ignored

$$F_g = \left[ 1 + \left( \frac{v_e}{v} \right)^2 \right], \quad (10.20)$$

where  $v_e$  is the escape velocity from the embryo, and  $v$  is the relative velocity of the embryo and the accreting planetesimal. Effects of the central star were introduced by Greenzweig & Lissauer (1992).

The gravitational focusing factor  $F_g$  is determined (numerically) by computing the planet's growth, the dynamics and mass function of the planetesimals, and the structure of the gas disk. The gravitational influence of the planetary embryo, as well as interactions among planetesimals, stirs up the velocities of the planetesimals, reducing  $F_g$  (Fortier et al., 2013).

The large number of planetesimals in the *feeding zone* ( $\geq 10^{10}$ ) requires that their evolution, growth, and accretion onto the embryo is treated statistically (e.g. Inaba et al., 2003; Weidenschilling, 2008; Kobayashi et al., 2010, 2011; Bromley & Kenyon, 2011b; Weidenschilling, 2011). Planetesimals are distributed in radial zones, and into a number of mass bins, with sizes ranging from tens of meters to tens of km. Numerical codes calculate the evolution of sizes and orbital elements, as well as the accretion rate of each size onto the planetary embryo. Sizes evolve through collisions and, for large relative velocities, through fragmentation (e.g. Guilera et al., 2014).

Velocities are affected by gravitational perturbations, viscous stirring and dynamical friction (footnote, page 3), and damping by gas drag. Object fragmentation depends on specific impact energies, material strengths, and gravitational binding energies. Other complications include planetesimal migration, and interactions between the protoplanetary envelope and the various-sized planetesimals.

**Isolation mass** In the absence of migration, the parameters most influencing formation are  $\sigma_s$ ,  $M_{\star}$  and  $a$ , which together determine the *isolation mass* (Pollack et al., 1996)

$$M_{\text{iso}} = \frac{8}{\sqrt{3}} (\pi C)^{3/2} M_{\star}^{-1/2} \sigma_s^{3/2} a^3, \quad (10.21)$$

which gives the maximum mass to which the embryo can grow, at which point it has accreted all of the planetesimals in its feeding zone.  $C$  is the number of Hill sphere radii on each side of the

planet included in the feeding zone.  $M_{\text{iso}}$  must exceed  $\sim 3M_{\oplus}$  for accretion to deliver a Jupiter-mass object during the disk lifetime. Although a minimum core mass of  $\approx 10M_{\oplus}$  is often considered necessary to initiate rapid gas accretion, the critical core mass depends on the disk properties, the detailed physical effects included, and the core accretion rate, and mean critical values may be closer to  $5M_{\oplus}$  (e.g. Hasegawa & Pudritz, 2014). Additional dependencies include the gas-to-solid ratio in the disk, which for solar composition is of order 100, but which decreases with increasing stellar metallicity. The gas surface density determines  $\rho_{\text{neb}}$ , and a disk model determines  $T_{\text{neb}}$ . The planetesimal size distribution and composition influence  $M_{\text{core}}$ . Models have also considered the simultaneous growth of nearby (Jupiter/Saturn-like) embryos (Guilera et al., 2010).

**Envelope accretion** The envelope accretion rate is influenced by the *Hill radius*,  $R_{\text{H}} = a(M_{\text{p}}/3M_{\star})^{1/3}$  (box, page 512), and the *Bondi radius*,  $R_{\text{B}} = GM_{\text{p}}c_s^{-2}$ , where  $c_s$  is the sound speed (e.g. Kanagawa & Fujimoto, 2013). The Bondi radius was originally formulated as an effective area for spherical accretion onto a star moving through the interstellar medium (Bondi, 1952), and is related to the object's escape velocity. For a planet forming in a protoplanetary disk, gas must fall into its Bondi sphere to accrete. For a massive planet, accreted gas can quickly fill the Bondi sphere, at which point the atmosphere must cool and contract for it to accrete further.

Simulations of the gas flow around a planet embedded in a disk show that not all of the gas flowing through the Hill radius is accreted by the planet, and that a modified radius  $\sim 0.25R_{\text{H}}$  better specifies the accretion cross section (Lissauer et al., 2009). Together these define an effective outer radius

$$R_{\text{eff}} = GM_{\text{p}} \left[ c_s^2 + \frac{GM_{\text{p}}}{0.25R_{\text{H}}} \right]^{-1}. \quad (10.22)$$

In early evolutionary phases, when  $M_{\text{env}} \leq M_{\text{core}}$ , the gas accretion rate is set by the requirement that  $R_{\text{p}} = R_{\text{eff}}$ . As the envelope contracts and  $R_{\text{eff}}$  expands, gas is added at the outer boundary to maintain this condition.

Once the planet has entered the phase of rapid gas accretion, the envelope is relatively massive, and it can contract rapidly. At some point, the mass addition rate exceeds the rate at which matter can be supplied by the disk. The disk-limited rates are calculated from 3d simulations (e.g. Lubow & D'Angelo, 2006; Benvenuto et al., 2007; Lissauer et al., 2009; D'Angelo et al., 2010; Machida et al., 2010; Bodenheimer et al., 2013; Kanagawa & Fujimoto, 2013; Nelson & Ruffert, 2013; Uribe et al., 2013; Coleman & Nelson, 2016a; Sirono & Katayama, 2016; Tanigawa & Tanaka, 2016). The rates are eventually limited as  $M_{\text{p}}$  grows, exerts tidal torques on the disk, and opens up a gap. Although gas can still accrete through the gap, the rate becomes slower as the gap width increases. Planet-disk interactions can excite eccentricities and increase  $\dot{M}_{\text{env}}$ , even after gap formation (Kley & Dirksen, 2006).

**Structure and evolution of the envelope** The gaseous envelope is typically considered to consist mainly of H+He, with a small fraction of heavy elements of stellar, substellar, or super-stellar metallicity. If all planetesimals reach the core without depositing mass in the envelope, the latter is likely to retain a composition similar to the gas in the protoplanetary disk. However, the accreted gas could be depleted in solids as a result of planetesimal formation. On the other hand, if planetesimals suffer strong mass ablation as they move to the core, the planetary envelope may be enriched with heavy elements compared to the disk gas, in particular during the first phases of growth when the solid accretion rate can be much larger than the gas accretion rate.

Models typically assume that the envelope is spherically symmetric, and the stellar structure equations of hydrostatic equilibrium, energy transport by radiation or convection, and energy conservation are used to determine its structure. During phases when  $R_p = R_{\text{eff}}$ , the density and temperature at the outer boundary are set to the disk values  $\rho_{\text{neb}}$  and  $T_{\text{neb}}$ .

The differential equations of stellar structure are then supplemented with the relevant equation of state and the opacity. The grains in the envelope are typically assumed to have an interstellar size distribution. However, when grain coagulation and envelope sedimentation are considered, grain opacities can drop from near interstellar values at the surface, by orders of magnitude deeper in the envelope (Podolak, 2003).

The capture and deposition of planetesimal material has significant effects on the composition, mean molecular weight, opacity, and equation of state of the envelope (e.g. Podolak et al., 1988; Mordasini, 2014; Venturini et al., 2015; Soubiran & Militzer, 2016), as supported by the threefold solar metallicity measured in Jupiter's atmosphere by the Galileo entry probe (Wong et al., 2004). Details of mass ablation are complex, and depends on (poorly known) characteristics including their mass and mechanical properties. In turn, envelope enrichment has a strong influence on the subsequent growth by gas accretion, and envelope enrichment can significantly reduce the critical mass required to initiate rapid gas accretion (e.g. Hori & Ikoma, 2011; Venturini et al., 2015).

It is often assumed that the ablated planetesimal material eventually sinks to the core, releasing gravitational energy. Detailed calculations show that for particular envelope models the rocky or organic components do sink, while ices remain dissolved in the envelope (Iaroslavitz & Podolak, 2007). Effects of convection, and the possible erosion of an initial heavy-element core, are detailed by Vazan et al. (2015).

Instead of gradual planetesimal accretion, Broeg & Benz (2012) considered episodic impacts of large mass ratio. They found that gas can be accreted faster for the same net core growth, while rapid gas accretion can occur for smaller cores. Significant envelope mass fractions can also be ejected, removing accretion energy, decreasing the formation time, and resetting the envelope composition to nebula conditions.

**Hydrodynamic collapse** Under certain combinations of core masses and opacities, the protoplanet envelope can undergo *hydrodynamic collapse*, in which gravity acting to contract it onto the core wins out over gas pressure acting to support it (e.g. Perri & Cameron, 1974; Mizuno, 1980). In the simulations of high-mass ( $15\text{--}33M_{\oplus}$ ) core accretion by Ayliffe & Bate (2012), such a collapse causes the density near the core to increase by a factor 10, the outer envelope to evolve into a circumplanetary disk, a new hydrostatic equilibrium for the envelope, and a subsequent resumption in accretion at its prior rate.

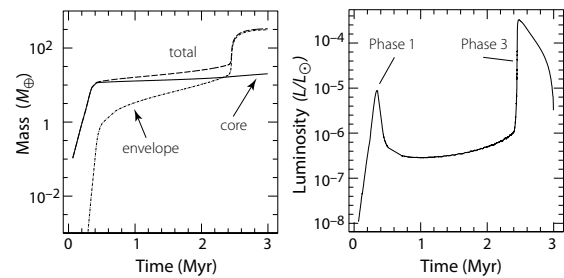


Figure 10.18: Growth of a protoplanet by core accretion (from Helled et al., 2014, Figure 1). The body is at 5.2 au, in a disk with  $\sigma_s = 10^2 \text{ kg m}^{-2}$ . Left: mass as a function of time, showing the core mass, envelope mass, and total mass. Grain opacities are reduced by a factor 50 from interstellar values. The crossover mass is reached at 2.3 Myr, and  $1M_J$  at 3 Myr. Right: radiated luminosity as a function of time. The first luminosity peak represents the maximum of  $\dot{M}_{\text{core}}$  during phase 1, while the second corresponds to the maximum disk-limited gas accretion rate during phase 3. From *Protostars and Planets VI* edited by Henrik Beuther, Ralf S. Klessen, Cornelis P. Dullemond, and Thomas Henning. ©2014 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press.

**Hot start, cold start, and entropy** During the disk-limited accretion phase, the gas envelope comprises a hydrostatic contracting inner region, containing almost all the mass, plus a supersonic hydrodynamic accretion flow of gas from the disk (Stahler et al., 1980; Bodenheimer et al., 2000). The properties of the shock affect the entropy of the gas that is finally accreted by the forming planet, which depends on the fraction of incoming energy radiated away through the shock (and which therefore does not end up as internal energy of the planet). This in turn governs the evolution of the post-formation luminosity (Marley et al., 2007b; Mordasini et al., 2012c; Marleau & Cumming, 2014; Marleau et al., 2017, their equation 1).

In *cold start* models, it is assumed that the gravitational potential energy released by the gas freely falling onto the planet is radiated away efficiently in the shock at the object's surface. This causes the gas to lose its initially high entropy, and leads to its incorporation into the object at a low specific entropy. In *hot start* models, the energy of the accreting body is given by the sum of its existing internal energy, fully supplemented by the gravitational energy of the accreting gas. Such models are initially warmer and have higher entropy (Marley et al., 2007b; Mordasini et al., 2012c; Mollière & Mordasini, 2012; Berardo & Cumming, 2017).

Details depends on the efficiency of energy radiation through the shock, and on the core mass of the planet at the end of accretion (e.g. Bodenheimer et al., 2013). For example just after formation, a  $12M_J$  planet (typical of inferred masses for directly imaged planets) could have  $\log L/L_{\odot} = -4.8 \rightarrow -6.6$ , corresponding to a core mass in the range  $31 \rightarrow 4.8M_{\oplus}$ . For lower final masses or higher core masses, the luminosities can be even higher (Mordasini, 2013).

Both models eventually converge to the same track of radius or luminosity versus time, but at young ages the results can be quite different. Planets of  $1M_J$  converge to the same track after 20 Myr, while  $10M_J$  planets take over  $10^9$  yr to converge (Marley et al., 2007b). Thus young, relatively massive planets calculated according to the 'cold start' are considerably fainter than those, at the same age, calculated with the 'hot start'.

The inability of current formation models to predict the initial entropy implies an associated uncertainty in the use of ‘hot-start’ or ‘cold start’ cooling tracks to interpret direct imaging observations in terms of luminosity and age (e.g. Spiegel & Burrows, 2012). Further constraints on mass for various imaged systems has led to estimates of their initial entropy (at the start of the pure cooling phase) for 2M 1207 b, HR 8799, and  $\beta$  Pic b of  $S_i > 9.2$ ,  $> 9.2$ , and  $> 10.5 k/\text{baryon}$ , where  $k$  is Boltzmann’s constant (Marleau & Cumming, 2014, and their Figure 8). At  $0.5 - 1.5 k/\text{baryon}$  higher than those obtained from core accretion models by Marley et al. (2007b), they rule out the coldest starts for these objects, and provide some constraints on warm starts, especially for  $\beta$  Pic b. For comparison Jupiter, at 4.5 Gyr, has a current entropy of  $7 k/\text{baryon}$  (Marley et al., 2007b).

Similar modeling has been used to support cold start core accretion, with  $M_{\text{core}} \sim 15 - 127 M_{\oplus}$ , for 51 Eri (Rajan et al., 2017), and to infer a planet mass of  $11.9 M_J$  (hot start) or  $14.0 M_J$  (cold start) in the case of HD 106906 (Daemgen et al., 2017a).

**Effects of migration** The general phenomenon of planet migration within a residual gas disk is considered in Section 10.10.2. Specific simulations indicate that migration significantly modifies the time scale and outcome of core formation and growth (Ward, 1989; Papaloizou & Terquem, 1999; Tanaka & Ida, 1999; Alibert et al., 2004, 2005a; Chambers, 2006a; Kornet & Wolf, 2006; Thommes & Murray, 2006; Crida et al., 2007; Edgar, 2007; Thommes et al., 2007; Chambers, 2008; D’Angelo & Lubow, 2008; Hasegawa & Pudritz, 2011b).

As examples, Rice & Armitage (2003) showed that, with stochastic migration due to turbulent disk fluctuations, the formation of Jupiter can be accelerated by almost an order of magnitude if the growing core executes a random walk with an amplitude of  $\sim 0.5$  au. Conversely, predicted migration rates place constraints on the disk mass and, in turn, on the likely parameters of the minimum-mass solar nebula (§10.3) in the case of the solar system (Desch, 2007; Crida, 2009).

Alibert et al. (2004) investigated how orbital migration can prevent the planet from reaching isolation (with the same effect also appearing as a result of the orbital drift of planetesimals by gas drag). As a consequence, the slow envelope accretion phase (phase 2) is suppressed, and a forming planet could evolve directly from phase 1 to phase 3, with the total formation time scale substantially reduced. This process is illustrated in Figure 10.19 which shows the formation of a Jupiter-mass planet for two models which are identical except that one assumes *in situ* formation (dashed lines), while second includes planetary migration (solid lines). In the migrating case, the initial planetary location is 8 au with  $\sigma_s = 32 \text{ kg m}^{-2}$ , and the planet migrates down to 5 au, where the *in situ* model is computed with  $\sigma_s = 75 \text{ kg m}^{-2}$ . For the *in situ* model, the crossover mass is reached after  $\sim 50$  Myr while in the migrating model, crossover mass is reached in less than a million years. When migration is included the total amount of heavy elements is increased by a factor  $\sim 2$ . Both models are computed assuming the same disk mass, which is around three times the minimum-mass solar nebula (§10.3), compatible with disk-mass estimates from observations (Andrews et al., 2011b).

Simulations of migration with accretion (from the inner Hill sphere) show that a fast migrating planet can accrete more gas, with some gas crossing the gap from the inner to the outer disk (Dürmann & Kley, 2015, 2017).

**Core accretion at larger radial distance** In the absence of migration, the optimum location for core accretion formation of a giant planet is between 5–10 au for  $M_{\star} = 1 M_{\odot}$ .

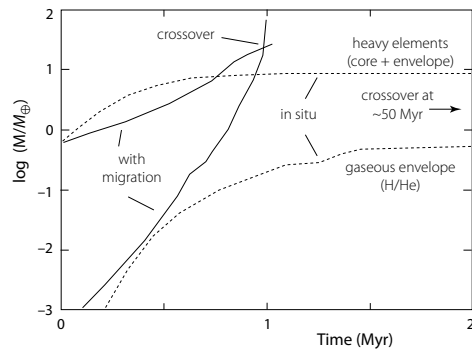


Figure 10.19: Mass of heavy-elements (core+envelope) and gas-envelope (H/He) versus time until crossover mass is reached (Helled et al., 2014, Figure 2). Solid lines show a migrating planet starting at 8 au, without gap formation. Dashed lines are for *in situ* formation. From *Protostars and Planets VI* edited by Henrik Beuther, Ralf S. Klessen, Cornelis P. Dullemond, and Thomas Henning. ©2014 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press.

At large orbital distances of  $\geq 30 - 50$  au, where giant planets have been imaged in systems such as HR 8799,  $\beta$  Pic, Fomalhaut, and LkCa 15 (§7.9), estimates of formation prospects via core accretion vary widely. In these regions, planetesimal number densities are low (Goldreich et al., 2004b), and building up the core by collisions between km-sized planetesimals may take  $> 10^7$  yr (Haisch et al., 2001; Currie et al., 2009).

Rafikov (2011a) estimated the maximum distance at which a giant planet can form, through gas runaway within a typical disk lifetime in a minimum-mass solar nebula, as 40–50 au, based on the assumption of a maximum rate of planetesimal accretion onto the core. A maximum for 20 au was found by Xiao & Jin (2015). Minimum core masses, if no longer accreting (and being heated by) planetesimals, decline with disk radius, from 8– $8.5 M_{\oplus}$  at 5 au to 3.5– $5 M_{\oplus}$  at 100 au, also depending on the equation of state (Piso & Youdin, 2014; Piso et al., 2015). Formation has been suggested via growth of a circumplanetary disk, with the entropy of the accreted material determined by boundary layer processes (Owen & Menou, 2016).

**Very wide orbits** Other mechanisms have been suggested to move giant planets, once formed, out to very wide orbits. In one model, icy cores accrete from planetesimals at  $\leq 30$  au, from where they are scattered outward by an emerging nearby gas giant to acquire highly eccentric orbits, thereafter circularised through the accretion of disk gas in outer regions (Kikuchi et al., 2014; Higuchi & Ida, 2017). Guilera et al. (2017) showed that photoevaporative gap opening can be accompanied by synchronised migration, resulting in an efficient outward migration of  $M_p \lesssim 1 M_J$  planets out to  $\sim 130$  au.

**Core accretion at small radial distance** In the very inner regions of disks at  $\sim 0.05$  au, *in situ* formation of hot Jupiters presents various difficulties for models of core accretion: the temperatures are high, resulting in little condensable material; the typical mass distribution in the inner disk provides insufficient material to form the 5– $10 M_{\oplus}$  cores necessary for giant planet formation; even if a planet did form, it would very likely migrate into the star unless the inner disk has been cleared, e.g. by the stellar magnetic field (Kley et al., 2009; Hellary & Nelson, 2012). The general picture is that hot Jupiters formed in the 5–10 au region, and subsequently migrated inwards (§10.7.1).

An early suggestion to circumvent these problems is to build the core by the inward migration of planetesimals to some collection region in the inner disk (e.g. Ward, 1997b; Bodenheimer et al., 2000).

In an extension of the models proposed for the (multiple) tightly-packed inner planets (§10.7.3), Boley et al. (2016) have suggested that these (typically super-Earth mass) systems form frequently, but metastably, with the time scale of dynamical instability having a major influence on final planet types. In most cases, the planets consolidate into a system of fewer, more massive planets, long after the circumstellar gas disk has dissipated, yielding short-period giants above the traditional critical core of  $\sim 10M_{\oplus}$ , but lacking abundant gas. If dynamical consolidation occurs before gas dispersal, a critical core can form that grows via gas capture into a short-period gas giant. Some evidence for limited consolidation has been found in the Kepler spacings (Pu & Wu, 2015). In a related *in situ* formation scenario, such transiting hot Jupiters should be accompanied by additional (but typically non-transiting) low-mass planets with  $P \lesssim 100$  d (Batygin et al., 2016).

**Magnetospheric accretion** Young gas giants are likely to possess strong dynamos driven by rapid rotation and significant convective motions in their interiors. Large-scale magnetic fields produced by these dynamos could channel accretion onto the giant planet, potentially producing observational signatures analogous to those observed in young stars. Lovelace et al. (2011) found that the effect is unimportant in the main accretion phase, in which thermal energy from accretion inflates their envelopes to sizes much larger than their magnetic Alfvén radius, but may be relevant at later phases.

**Termination of accretion** The termination of rapid gas accretion may result from disk dissipation, or from gap opening. For the former, the general picture of disk evolution involves a gradual reduction in disk mass and disk gas density over 2–4 Myr, after which a relatively rapid (few  $10^5$  yr) clearing phase occurs (§10.3.6).

**Gap opening** For planets that reach the phase of rapid gas accretion, gap opening plays a critical role. Once the forming planet reaches a sufficient mass, its gravitational influence results in a torque on disk material interior to the planet's orbit, removing angular momentum from the material and allowing it to move closer to the star. At the same time, material exterior to the planet's orbit gains angular momentum and is moved to larger distances. As a result a gap, or at least a region of lower density, tends to form near the planet's orbit (§10.10.2).

Even after gap opening, gas can still flow across it and accrete onto the planet, but at a decreased rate (e.g. Lubow et al., 1999; D'Angelo et al., 2002). The peak in  $\dot{M}_{\text{env}}$  occurs for  $M_{\text{p}} \sim 0.1 - 1M_{\text{J}}$  around a solar-mass star, depending on the viscosity. Beyond that point, gas continues to be accreted through the gap until its density is reduced by a factor 1000, leading to a final planet mass of up to  $5 - 10M_{\text{J}}$  for  $\alpha \approx 4 \times 10^{-3}$ . Further accretion is possible in an eccentric orbit.

The maximum planet mass in the core accretion model therefore appears to correspond to the highest masses observed. Planets of Jupiter–Saturn mass would have to be formed in a disk region with low temperatures (low  $H/a$ ) and low viscosity. Angular momentum transferred from the disk to the planet during the gap-opening process may lead to a sub-disk around the planetary core (Ayliffe & Bate, 2012).

The limiting gas accretion rate depends on the disk viscosity and gas surface density. The latter evolves on time scales

comparable to that of buildup of planetary cores (a few Myr). As a consequence, at a time when the critical mass is reached, the limiting accretion rate has decreased by up to two orders of magnitude, compared to a classical young disk, reaching values  $\sim 10^{-4}M_{\oplus}/\text{yr}$  or lower. Under these circumstances, the accretion of  $1M_{\text{J}}$  takes  $\approx 3$  Myr, comparable with disk lifetimes. Such calculations have been used to explain the heavy element mass in Jupiter and Saturn (Alibert et al., 2005d), as well as the observed mass function of exoplanets (Mordasini et al., 2009a,b). An example is the model shown in Figure 10.18, which reached a final mass of  $1M_{\text{J}}$  without any assumed cut-off, in a disk with viscosity parameter  $\alpha = 4 \times 10^{-4}$  and a disk lifetime of 3 Myr.

**Dependence on stellar mass** Typical observed disk masses decrease roughly linearly with the mass of the central star from  $M_{\star}$  of a few solar masses down to less than  $0.1M_{\odot}$  with a typical  $M_{\text{disk}}/M_{\star} = 0.002 - 0.006$  (Andrews et al., 2013). However, observed disk masses show a large spread at a given stellar mass, from  $0.001 - 0.1M_{\odot}$  for a  $1M_{\odot}$  star. Furthermore, disk masses are uncertain because they are determined from dust continuum observations, which do not measure the gas mass and which are affected by uncertainty in the dust opacity. Characteristic disk lifetimes extend from a median of 3 Myr to a maximum of 10 Myr (Hillenbrand, 2008). Separating out the disk dispersal times as a function of mass has proved to be difficult (Kennedy & Kenyon, 2009; Ribas et al., 2015). To a first approximation, disk lifetimes are independent of stellar mass for  $M_{\star} < 1.5M_{\odot}$ , but decrease for  $M_{\star} > 1.5M_{\odot}$ , possibly because of more effective dissipation by ultraviolet and X-ray irradiation (§10.3.6). Again, for a given stellar mass, there is a range of disk lifetimes, from about 1–10 Myr.

If the disk mass in solids scales with  $M_{\star}$ , then the solid surface density around low-mass stars is expected to be smaller, leading to slower formation (and conversely around higher mass stars). In addition, the dynamical time  $\Omega^{-1}$  is longer, resulting in longer accretion times. Thus it should be more difficult to form a Jupiter-like planet at a given radial distance around a low-mass star than around a solar-mass star (Laughlin et al., 2004a), on a time scale comparable to the characteristic 2.5 Myr lifetime of disks around low-mass stars (Mamajek, 2009). More detailed estimates confirm this picture (e.g. Ida & Lin, 2005b; Kornet et al., 2006; Alibert et al., 2011).

**Giant planets around M dwarfs** In line with the scaling of disk mass with  $M_{\star}$ , small planets ( $0.5 - 4R_{\oplus}$ ) are common around M dwarfs (e.g. Dressing & Charbonneau, 2013), while giants are relatively rare. A few have been found from radial velocities (the first three being GJ 876, GJ 849, and GJ 317), while only four transiting giant planets are known around M dwarfs: Kepler-45 ( $0.5M_{\text{J}}$ ), HATS-6 ( $0.3M_{\text{J}}$ ), WASP-80 ( $0.5M_{\text{J}}$ ) and NGTS-1 ( $0.8M_{\text{J}}$ ). Observational results suggest that the probability of a star hosting a planet  $\geq 0.5M_{\text{J}}$  is  $\propto M_{\star}$  (Johnson et al., 2010a). The overall frequency of 1– $10M_{\text{J}}$  planets has been estimated as 0.07 planets per M dwarf (Meyer et al., 2017). Meanwhile, microlensing surveys suggest that many M dwarfs may possess giant planets at larger distances (Gould et al., 2010b).

**Giant planet occurrence versus stellar metallicity** Of importance in constraining formation models, there is a well-established correlation of giant planet occurrence with stellar metallicity for main sequence stars from  $0.3 - 2M_{\odot}$  and  $-1.0 < [\text{Fe}/\text{H}] < 0.5$  (e.g. Gonzalez, 1997; Santos et al., 2004c; Fischer & Valenti, 2005; Johnson et al., 2010a; Mortier et al., 2013a; Maldonado et al., 2013; Schlaufman, 2014; Maldonado & Villaver, 2016). From a radial velocity sample of 1040 FGK stars,



Fischer & Valenti (2005) gave the probability as

$$P_{\text{gp}} = 0.03 \times 10^{2.0[\text{Fe}/\text{H}]} . \quad (10.23)$$

They argued that the dependence of  $P_{\text{gp}}$  on the square of the number of Fe atoms was the natural expectation from the collisional agglomeration of dust grains.

With 1111 FGK field and planet host stars from HARPS, Schlaufman (2014) derived, near  $[\text{Fe}/\text{H}] = 0$ ,

$$P_{\text{gp}}([\text{Fe}/\text{H}]) = 0.08^{+0.02}_{-0.03} \times 10^{(2.3 \pm 0.4)[\text{Fe}/\text{H}]} . \quad (10.24)$$

At lower mass, Neptune-mass ( $10 - 40M_{\oplus}$ ) planets from early radial velocity surveys did not appear to preferentially orbit metal-rich FGK stars (e.g., Sousa et al., 2008; Mayor et al., 2011), although a more recent combined sample of 157 planets from radial velocity and transit surveys shows a correlation of occurrence (and maximal planet mass) with host star metallicity (Courcol et al., 2016). Whether the correlation extends to (super-)Earth masses remains unclear (§10.3.6).

The broad picture is that disk metallicity increases with stellar metallicity. If the abundance of grain-forming material (ices, organics and silicates) increases with the Fe abundance, then a higher  $\sigma_s$  results at a given distance. Observations show, for example, that planet occurrence at a given  $[\text{Fe}/\text{H}]$  increases with the stellar Si abundance (Robinson et al., 2006a). The higher  $\sigma_s$  then gives a shorter formation time for the core at a given distance,  $\propto \sigma_s^{-0.5}$ .

Observationally, planets with masses between Earth and Neptune divide into two populations: purely rocky bodies whose atmospheres contribute negligibly to their sizes, and larger gas-enveloped planets with voluminous optically thick atmospheres. Dawson et al. (2015a) showed that disks with higher initial solid surface density breed massive rocky (accreting) cores more quickly, within the gas disk lifetime, and so produce gas-enveloped planets. In disks of low solid surface density, cores of suitable mass appear only after the gas disk has dissipated, and so remain purely rocky.

Challenges in constructing detailed metallicity-dependent models include effects of disk lifetime, viscosity, dust opacity in the envelope, and dependence on isolation mass (e.g. Ida & Lin, 2004b; Hori & Ikoma, 2010; Movshovitz et al., 2010; Mordasini et al., 2012a; Vazan et al., 2013; Hasegawa & Hirashita, 2014; Hasegawa & Pudritz, 2014; Helled et al., 2014; Keith & Wardle, 2014; Szulágyi et al., 2014).

**Heavy element contribution to planet mass** Knowledge of the heavy element contribution to  $M_p$  would provide important constraints on models of envelope accretion in giant planets, with a higher heavy element fraction expected to result in a smaller  $R_p$  at given  $M_p$ . In practice, use of masses and radii of transiting planets as a structural probe for giant planets is hindered by the fact that strongly irradiated planets ( $T_{\text{eq}} > 1000\text{ K}$ ) have radii (and hence interior temperatures) larger than predicted by simple cooling and contraction models (§6.28.4). With the additional interior energy largely unknown, the heavy element fraction is correspondingly unconstrained.

On the assumption that the inflation mechanism scales as the stellar flux incident, and with a sample size of nine planets, Guillot et al. (2006) showed that there is a strong correlation between stellar metallicity and the inferred mass of heavy elements, in the sense that the most Fe-rich stars possess the most heavy element rich planets. With a somewhat larger sample size, Burrows et al. (2007a) found a similar relation.

Miller & Fortney (2011) recognised that anomalously large radii disappear at incident fluxes  $\lesssim 2 \times 10^5 \text{ W m}^{-2}$  ( $T_{\text{eq}} \sim$

1000K). For a sample of 14 relatively cool planets, they found that all possess at least  $\sim 10 - 15M_{\oplus}$  of heavy elements, consistent with the enrichments of Saturn and Jupiter.

Thorngren et al. (2016) used an enlarged sample of 47 transiting giant planets with similarly low stellar insolation, and used structural and thermal models to demonstrate a correlation of heavy element mass  $\propto M_p$ , consistent with core accretion models. They concluded that the large heavy element masses of many planets ( $> 50M_{\oplus}$ ) suggests significant amounts in their H/He envelopes, rather than being simply restricted to their cores, and that it is  $M_p$  that determines the relative enrichment, and not the metallicity of the star.

Transits of the relatively small radius Saturn-mass planet HD 149026 (Sato et al., 2005a) show that even relatively low mass gas giants can possess  $60 - 90M_{\oplus}$  of heavy elements. Relatively small radii for massive giant planets from  $2 - 10M_J$  show that hundreds of  $M_{\oplus}$  of heavy elements must be incorporated into some planets (Baraffe et al., 2008; Miller & Fortney, 2011). Again, it seems likely that for massive giant planets with large enrichment in heavy elements, much of the heavy element mass is in the H/He envelope, rather than in a core.

**Post-formation evolution** Giant planet formation lasts for  $10^4 - 10^6$  yr. For  $M_p = 1M_J$ , the radius decreases to  $\sim 1.4R_J$  over  $\sim 10^5$  yr (Bodenheimer & Pollack, 1986; Bodenheimer et al., 2000). Following the end of accretion, the planet slowly contracts and cools at constant mass over many Gyr. The progressive decline in luminosity with time, and the  $L \propto M_p^2$  mass–luminosity relation, imply that prime targets for direct detection are relatively massive planets around younger stars.

For giant planets close to their host stars, additional energy sources including stellar irradiation, which inhibits energy release from the interior, and results in a larger radius than for an unirradiated planet at any given time (§8.10), and tidal dissipation caused by orbit circularisation and spin–orbit synchronisation (§10.11). These and numerous other effects which may modify the energy balance and resulting radii of close-in hot Jupiters are considered further in Section 6.28.4.

Continuing effects of dynamical instabilities, for example through planet–planet scattering, are considered in Section 10.10.4.

**Giant planet interiors** Knowledge of the interior structure and composition of giant planets would provide further constraints on formation processes. In the absence of gravity field or moment of inertia information, first insights come from transit and eclipse spectroscopy (§11.6), and from comparing models at a given mass and age with estimates of a transiting planet's mass and radius, which yield its mean density. Higher mean densities provide evidence that the planet is progressively enhanced in heavy elements.

From measurements of their mass and radius alone, it is evident that Jupiter and Saturn are enhanced in heavy elements compared to the Sun, without knowledge of their gravity field. For an exoplanet, it will not be immediately evident whether such heavy elements are predominantly within a core or mixed throughout the H/He envelope. The uncertain mechanisms responsible for the inflation of the radii of close-in planets further complicates interpretation of the mass–radius relation.

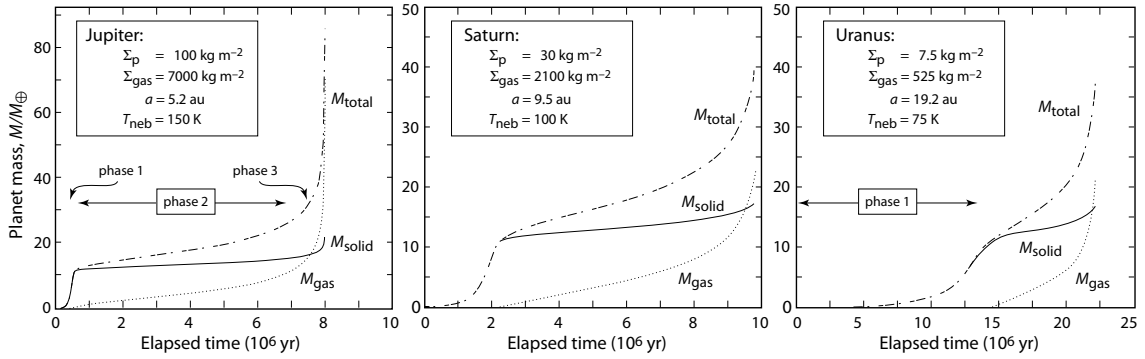


Figure 10.20: Giant planet formation by core accretion. Simulations correspond to Jupiter, Saturn, and Uranus (models J1, S1, and U1 from Table III of Pollack et al. 1996). Values shown are the initial conditions for the planetesimal and gas surface densities  $\Sigma_p$  and  $\Sigma_{\text{gas}}$ , the initial embryo semi-major axis  $a$ , and nebula temperature  $T_{\text{neb}}$ . Simulations begin with an embryo mass comparable to that of Mars, with almost all its mass in a high- $Z$  core. Planetesimals have a radius of 100 km. The results show, as a function of time, the total planet mass  $M_{\text{total}}$ , and the corresponding contributions from accumulated solids  $M_{\text{solid}}$ , and accumulated gas  $M_{\text{gas}}$  (dashed, solid, and dotted lines respectively). From Pollack et al. (1996, Figures 1, 4, 5), with permission from Elsevier.

**The solar system giants** Pollack et al. (1996) described early simulations of the formation of the solar system gas and ice giants within the framework of the core accretion model, which reproduce many of their principal structural features. More recent detailed model results are given in Section 12.2.2.

For phase 1, the growing planet, with an initial embryo mass corresponding to that of Mars, and with almost all its mass in a high- $Z$  core, is assumed to be embedded in a disk of gas and planetesimals (of radius 100 km), with a locally uniform initial surface mass density. The embryo accretion rate was derived from three-body (Sun, protoplanet, and planetesimal) orbital integrations, with a suitable distribution of planetesimal eccentricities and inclinations.

For phase 2, the growing importance of the gaseous envelope around the high- $Z$  core enhances the capture radius  $R_c$  (Equation 10.15), leading to the deposition of mass and energy within the envelope once the incoming planetesimal intercepts a mass of gas comparable to its own mass (Pollack et al., 1986).

For phase 3, the gas accretion rate is estimated from the core mass and radius at that time, assuming  $\rho_{\text{core}} = 3.2 \text{ Mg m}^{-3}$ , and based on equations of state and opacity coefficients using a solar mixture of elements, normal stellar opacities for  $T > 3000 \text{ K}$ , and opacity contributions from  $\text{H}_2\text{O}$ , silicates, Fe, and TiO at lower temperatures. Detailed considerations involve the transfer of angular momentum and rotational instabilities, contraction, and disk feedback (Ward & Canup, 2010).

Giant planet formation time scales consistent with the lifetime of the solar nebula (cf. Equation 10.15) are met for planetesimal surface densities  $\Sigma_p$  somewhat larger than those given by the minimum-mass solar nebula (§10.3), and if core growth occurs mainly during run-

away accretion when the effects of gravitational focusing can be very large,  $F_g \sim 10^4$  (Lissauer, 1987).

Their initial conditions assume specific values for the semi-major axis of the initial embryo orbit  $a$ , the nebula temperature  $T$ , the initial planetesimal surface density  $\Sigma_p$ , and initial gas surface density  $\Sigma_{\text{gas}}$ . Illustrative results are shown in Figure 10.20 for their (baseline) models for Jupiter, Saturn and Uranus. In each case, the results show, as a function of time, the total planet mass  $M_{\text{total}}$ , and the corresponding contributions from accumulated solids  $M_{\text{solid}}$ , and accumulated gas  $M_{\text{gas}}$ .

For Jupiter, growth actually occurs in three distinct phases. During phase 1, the first  $5 \times 10^5 \text{ yr}$ , the embryo accumulates solids by runaway planetesimal accretion, a process which ends with depletion of its feeding zone. During most of phase 2,  $\sim 7 \times 10^6 \text{ yr}$ , the accretion rates of gas and solids are reasonably constant. The planet's growth accelerates towards the end of this phase, and runaway accumulation of gas (and to a lesser extent solids) ensues during phase 3. The process ends when the supplies of planetesimals and gas terminate.

For Saturn, phase 1 lasts four times longer, while the overall duration of phase 2 is similar. For Uranus, phase 1 is a further factor of eight longer, while the overall duration is a factor 2–3 longer than for Jupiter.

For Uranus and Neptune (20–30 au), the core accretion time at their present location is so long that it is unlikely that they formed there (Pollack et al., 1996). It is now believed that they formed nearer in, at 5–20 au, and were later scattered outwards (§12.6). Even at these distances the formation time for the core would be long enough that substantial disk dissipation occurred during phase 2, with the result that they never reached the crossover mass, and their present bulk compositions can be explained as the result of the dissipation of the nebula gas while the planets were still in their long-lived phase 2.

In the simulations of Bodenheimer & Pollack (1986), critical core masses lie in the range  $10 - 30 M_{\oplus}$ . More recent estimates are rather in the range  $5 - 20 M_{\oplus}$ , and with a dependency on accretion rate,  $\dot{M}_{\text{core}}$ , and grain opacity,  $\kappa$ . Ikoma et al. (2000) give the analytical fit

$$M_{\text{core}}^{\text{crit}} \sim 7 M_{\oplus} \left( \frac{\dot{M}_{\text{core}}}{1 \times 10^{-7} M_{\oplus} \text{ yr}^{-1}} \right)^{q'} \left( \frac{\kappa}{0.1 \text{ m}^2 \text{ kg}^{-1}} \right)^s, \quad (10.25)$$

with exponents  $q'$  and  $s$  in the range 0.2–0.3. This dependency indicates that faster growth can be achieved, but at the expense of a larger core mass.

Observationally, the core masses of the solar system giant planets remain somewhat uncertain. It has been suggested that further downward revision of the estimated core masses for Jupiter and Saturn might challenge core accretion models, unless the cores dissipate following gas accretion (Guillot et al., 1997; Guillot, 1999a; Guillot et al., 2004; Helled & Schubert, 2008).

**Multi-planet systems** The model should be able to replicate the formation of multi-planet systems, using a consistent coupling between the processes of core accretion and inward migration. As one example, Alibert et al. (2006) proposed a formation scenario for the three-Neptune mass system HD 69830, in which the planets have masses of 10, 12, and  $18M_{\oplus}$ , with semi-major axes  $a = 0.08$  au, 0.19 au, and 0.63 au respectively.

Their model predicts that the innermost planet formed from an embryo which started inside the snow line (§11.2.3), and is composed of a rocky core surrounded by a small gaseous envelope. The two outermost planets started their formation beyond the snow line and, in consequence, accreted a substantial amount of  $H_2O$ -ice during their formation and subsequent migration. The current thermodynamical conditions inside the two outer planets suggests that they are made of a rocky core surrounded by a shell of fluid  $H_2O$ , contained within a more extended gaseous envelope. McNeil & Nelson (2010) were, however, unable to reproduce the observed distributions.

### 10.5.2 Gravitational disk instability

**Context** In the core accretion model, planets form ‘bottom-up’: microscopic dust in the protoplanetary disk grows into grains, grains progressively stick to make km-sized objects, and these ‘planetesimals’ collide and coalesce to form solid bodies up to terrestrial planet mass. If the core attains a critical mass,  $\sim 10M_{\oplus}$ , and does so rapidly enough that gas is still plentiful within the disk, a massive gas envelope can accrete from the residual disk.

In the 1980s, an alternative possibility was put forward for the formation of at least some giant planets: *gravitational disk instability*. This contrasting ‘top-down’ model held that giant planets could form, more directly, by contraction of gaseous condensations in a massive self-gravitating disk. Such a mechanism would circumvent various uncertainties inherent in the progressive accumulation of solids, from sub- $\mu\text{m}$  scales upwards, and would side-step the lengthier formation time scale implied by core accretion.

The fact that giant planets in the solar system are believed to contain massive solid cores (Stevenson, 1982a; Pollack, 1984; Fortney & Nettelmann, 2010) was taken as key supporting evidence for the core accretion model, and interest in the alternative scenario wavered. Boss (1998) meanwhile argued that such cores could also result from dust sedimentation inside gaseous protoplanets. He later showed that removal of the gas envelope by photoionisation due to, e.g., a nearby OB star could form the ice giants (Boss et al., 2002).

The essence of the early model is a rapid, largely single-step collapse in a massive, gravitationally unstable protoplanetary gas disk, which then leads to the formation of gas giant protoplanets. Coagulation and settling of dust grains forms ice-rock cores at their centres, while photoevaporation of their gaseous envelopes would form the ice giants (Kuiper, 1951; Cameron, 1978a; Bodenheimer et al., 1980a; Adams & Benz, 1992; Boss, 1995, 1997, 1998; Boss et al., 2002; Boss, 2003, 2005, 2006a,b,c,d, 2007b, 2008, 2010).

Of these two main models, gravitational instability has been the most contentious, and remains the least-widely embraced. The more recent appreciation of the role of inward migration following the formation of giant planet embryos further out in a gravitationally-unstable disk nonetheless provides a possible framework (termed ‘tidal downsizing’) for planet formation over a range of mass, composition, and orbit radius.

**Early studies** It has long been realised that thin accretion disks become gravitationally unstable at large radii, both around active galactic nuclei (Shlosman et al., 1990) and young stellar objects (Adams & Lin, 1993). Such disk models are characterised by their Toomre  $Q$  parameter (Equation 10.3), with  $Q > 1$  indicating stability, and  $Q \sim 1$  indicating (marginal) instability.

Early studies suggested that marginally unstable disks would evolve through the formation of spiral density waves (Laughlin & Bodenheimer, 1994), which would transport angular momentum, thereby lowering the surface density and enhancing stability (Lin & Pringle, 1990), but also leading to dissipation and heating, thereby raising the sound speed, and further resisting fragmentation (Cassen et al., 1981). Fragmentation then depends on whether the disk self-gravity can overcome the thermal pressure in the disk, which acts to damp the growth of perturbations (Hopkins & Christiansen, 2013; Takahashi et al., 2013).

For a disk with an aspect ratio  $h/r = 0.05$  at 10 au around a  $1M_{\odot}$  star,  $Q = 1$  requires a disk surface density  $\Sigma \sim 10^4 \text{ kg m}^{-2}$ . This is a factor two larger than that given by the minimum-mass solar nebula at the same radial distance (Equation 10.5), suggesting that the mechanism operates, if at all, preferentially at early epochs when the disk mass is still high.

The essence of the early gravitational instability model is captured in the 3d hydrodynamic simulations described by Boss (1997). The model starts with an axisymmetric disk of mass  $140M_J$  ( $0.13M_{\odot}$ ), orbiting a star of  $1M_{\odot}$ , and extending between 1–10 au (rotation period 1–28 yr). The disk is seeded with bar-like density perturbations, biasing it towards a two-arm spiral structure.

The disk is assumed to be either locally isothermal ( $\gamma = 1$  in the pressure–density relation  $P \propto \rho^{\gamma}$ ), or locally adiabatic ( $\gamma = 7/5$ , implying that the density enhancements are unable to cool radiatively during their growth

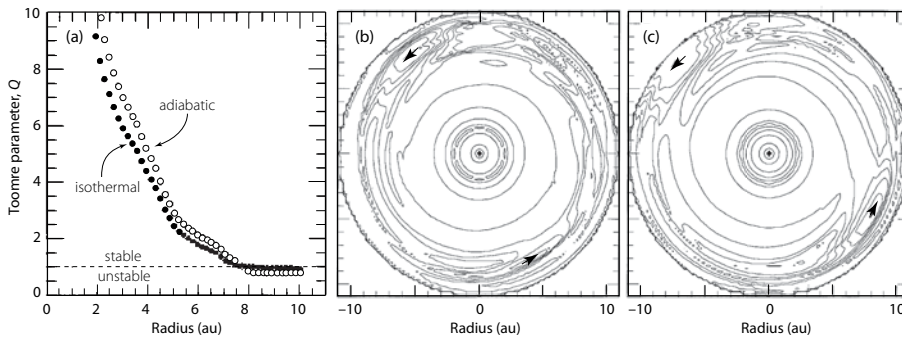


Figure 10.21: Giant planet formation by gravitational instability: (a) the Toomre stability parameter  $Q$  as a function of radius, at the start of the simulations, for both locally isothermal and locally adiabatic models. The horizontal dashed line shows the critical value,  $Q = 1$ , for instability to the growth of non-axisymmetric perturbations. Right pair: equatorial density contours in the 3d disk showing the outcome of (b) the locally isothermal model after 430 yr, and (c) the locally adiabatic model after 550 yr. Each disk forms two giant gaseous protoplanets, of unequal mass, with arrows denoting their centres and direction of motion. Each is trailed by a low-density region, and thin spiral arms. From Boss (1997, Figures 1–2), reprinted with permission from AAS.

phase). Over some 15 rotation periods of the outer disk, the inner disk regions remain stable ( $Q \gg 1$ ), becoming unstable ( $Q \sim 1$ ) at around 7.5 au in both cases (Figure 10.21). In both models, the initial bar-shaped perturbation winds up into a two-arm spiral. Self-gravity overcomes the thermal pressure, and each disk breaks up into two giant gaseous protoplanets (the number reflecting the form of the initial perturbations), with masses in the range  $1 - 8M_J$ . The Jeans mass, of around  $0.2 - 1M_J$ , is exceeded, and further collapse follows.

Boss (1997) argued that, at solar composition, a  $1M_J$  protoplanet region contains  $\sim 6M_{\oplus}$  of elements heavier than H/He. During the subsequent  $10^5$  yr of contraction to planetary densities, slowed by the gas pressure, dust grains grow by collisional coagulation and sedimentation, along the lines expected for terrestrial planet formation, forming a substantial rock and ice core.

**Cooling** Numerical experiments by Gammie (2001) showed that cooling, characterised by the cooling time  $\tau_c$ , controls the instability: if  $\tau_c \geq 3\Omega^{-1}$  then the disk reaches a steady gravito-turbulent state in which  $Q \sim 1$  and cooling is balanced by heating due to dissipation of turbulence, while if  $\tau_c \lesssim 3\Omega^{-1}$ , then the disk fragments. The same fragmentation boundary was confirmed in 3d hydrodynamic simulations by Rice et al. (2003b, 2005). With fragment contraction times as long as  $10^5 - 10^7$  yr, the fragments may be tidally destroyed before contracting into gas giant planets.

The challenge for gravitational instability models is then not *whether* protoplanetary disks are unstable at large radii, but whether instabilities fragment into self-gravitating clumps of gas and dust, the detailed fate of these clumps, and the model's relevance to (giant) planets within 20–40 au. Definitive answers are elusive because of the large number of variables and unknowns, including disk opacity, dust physics, angular momen-

tum of the infalling material, mass deposition rate into the disk, and the background radiation field.

**Detailed results** To summarise many detailed studies somewhat simplistically, later work has generally confirmed that massive ( $\geq 0.1M_{\odot}$ ) protoplanetary disks should cool rapidly enough to become gravitationally unstable, and to fragment, beyond a few tens of au (depending on detailed model parameters), while fragmentation appears less likely to produce giant planets around solar-type stars at  $\leq 40$  au, where the gas cools too slowly for it to fragment into bound clumps. Models have incorporated a range of disk structures, dust layers, opacities, dead zones, and infall rates, as well as Kelvin–Helmholtz instability, particle-driven turbulence, radiative feedback, density waves, Hill radius, and triggering by rapid impulsive events (e.g. Mayer et al., 2004; Matzner & Levin, 2005; Rafikov, 2005; Boley et al., 2006, 2007; Clarke et al., 2007; Durisen et al., 2007; Mayer et al., 2007; Michikoshi et al., 2007; Rafikov, 2007; Durisen et al., 2008; Helled et al., 2008; Helled & Schubert, 2008; Stamatellos & Whitworth, 2008; Clarke, 2009; Rafikov, 2009a; Rice & Armitage, 2009; Cai et al., 2010; Cossins et al., 2010; Inutsuka et al., 2010; Kratter et al., 2010b; Lee et al., 2010a,b; Lizano et al., 2010; Mayer, 2010; Meru & Bate, 2010; Michikoshi et al., 2010; Rice et al., 2010; Vorobyov & Basu, 2010a; Boley et al., 2011; Forgan & Rice, 2011; Meru & Bate, 2011b,a; Rogers & Wadsley, 2011; Youdin, 2011a; Boss, 2012a; Gibbons et al., 2012; Kimura & Tsuribe, 2012; Vazan & Helled, 2012; Vorobyov, 2013; Rice et al., 2015; Rice, 2016; Riols & Latter, 2016; Shi et al., 2016; Takahashi et al., 2016; Young & Clarke, 2016; Klee et al., 2017; Liu et al., 2017b).

Other studies have examined aspects of chemical enrichment and differentiation, and metal enrichment by planetesimal capture and tidal stripping, which may serve as tests for gravitational instability models (Boley & Durisen, 2010; Ilee et al., 2017).

**Hybrid models** With results somewhat divided as to the regimes in which giant planet formation by gravitational instabilities may occur, the possibilities of dual or hybrid models were also suggested. Matsuo et al. (2007) argued, for example, that 90% of the planets known at the time are consistent with core accretion, with 10% demanding disk instability, while oth-

ers have described hybrid scenarios where gravitational instabilities facilitate core accretion (Durisen et al., 2007; Inutsuka et al., 2010). Boley (2009) argued that giant planets at  $r > 100$  au are likely to form *in situ* by disk instability, while core accretion plus gas capture is the dominant formation mechanism for  $r < 100$  au. This should lead to a bimodal distribution of gas giant semi-major axes and, because core accretion is expected to be less efficient in low-metallicity systems, the ratio of gas giants at large  $a$  to planets at small  $a$  should increase with decreasing metallicity.

**Bursts and migration** Simulations by Mejía et al. (2005) showed a ‘burst’ of FU Ori-like mass accretion onto the central protostar, related to the growth of spiral instability and dense clumps within the arms. Further simulations (Vorobyov & Basu, 2005, 2006, 2010a,b) led to a ‘burst mode’ model of cloud core collapse in which the infall of matter from the surrounding envelope can periodically destabilise the disk and lead to the formation of spiral structure and dense clumps within the arms. Gravitational torques associated with the spiral arms then drive the clumps onto the protostar, generating mass accretion, and FU Ori-type luminosity bursts. The simulations give prolonged periods of low accretion ( $\leq 10^{-7} M_{\odot} \text{ yr}^{-1}$ ), punctuated by intense bursts of high accretion ( $\geq 10^{-4} M_{\odot} \text{ yr}^{-1}$  over a duration  $\leq 100$  yr) during which most of the protostellar mass is accumulated. The accretion bursts are associated with the formation of dense embryos, which are later driven onto the protostar by gravitational torques in the disk, transporting mass inward and angular momentum outward.

Boley et al. (2010) found that initial fragments in the gas giant mass range have substantial angular momentum, which should form disks with radii of a few au. Clumps survived for multiple orbits before undergoing a second rapid collapse due to  $\text{H}_2$  dissociation. Bound clumps could be destroyed by delivery into the inner disk, while  $\sim 1 M_{\oplus}$  cores could be formed in the outer disk during the earliest evolutionary phases.

Subsequent simulations, invoking dust sedimentation, have also identified robust clump formation followed by inward migration and tidal destruction (Font-Ribera et al., 2009; Nayakshin, 2010a,b; Baruteau et al., 2011b; Cha & Nayakshin, 2011; Machida et al., 2011; Michael et al., 2011; Nayakshin, 2011a; Zhu et al., 2012a). Other work found that (non-migrating) brown dwarfs dominated (Stamatellos & Whitworth, 2008, 2009), although including radiative feedback may change such findings (Nayakshin & Cha, 2013).

Some simulations have aimed to replicate the large-separation planets around HR 8799 and Fomalhaut (Dodson-Robinson et al., 2009; Nero & Bjorkman, 2009; Boss, 2011b; Zhu et al., 2012a), and to the consequences for the metallicity dependence in planets and debris disks, particularly when incorporating pebble accretion (Nayakshin, 2015b; Fletcher & Nayakshin, 2016).

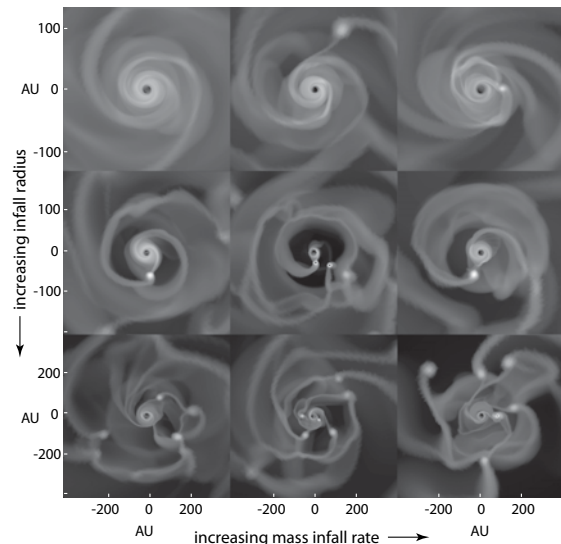


Figure 10.22: Planet formation by gravitational instability: 2d hydrodynamical simulations of the disk surface density are shown for different infall rates (from  $\sim 3 \times 10^{-5}$  to  $3 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ , left to right) and infall radii (from 65 to 200 au, top to bottom). At a given infall rate, spiral arms become more unstable with increasing infall radius, and eventually break into fragments. At marginal fragmentation only one clump forms, while higher infall rates lead to more unstable arms, with more pronounced fragmentation and multiple clumps. From Zhu et al. (2012a, Figure 1), by permission of IOP Publishing/AAS.

**Tidal downsizing** This scenario has been termed *tidal downsizing*, in which inwardly migrating giant planet embryos are tidally stripped to reveal their final planet form. As described by Nayakshin (2010a), and quantified by these simulations, it begins with the fragmentation, at several tens to hundreds of au, of a massive young protoplanetary disk into gaseous clumps with masses of a few  $M_J$ . The clumps cool and contract, and simultaneously migrate closer to the parent star due to gravitational interactions with the gas disk.

The condition that clumps fragment when the disk-cooling time is no longer than a few times the local dynamical time limits the fragmentation region to  $R \geq 30 - 100$  au (e.g., Rafikov, 2005; Stamatellos & Whitworth, 2008; Meru & Bate, 2010). At the point of marginal gravitational stability the density in the disk mid-plane is about the tidal density at that point,  $\rho_t = M_{\star} / (2\pi R^3)$ . Thus, at fragmentation, the cooling time is of order the free-fall time,  $t_{\text{ff}} \sim 1 / \sqrt{G\rho}$ . As the clumps contract further, their cooling time becomes longer than their free-fall times. The initial state of a giant embryo is that of a polytropic clump (Cameron et al., 1982), similar to the ‘first cores’ studied in the context of star formation (Larson, 1969; Masunaga & Inutsuka, 2000).

Nayakshin (2010a) assumed subsequent evolution at constant mass, determining the radiative cooling as

a function of dust opacity, sedimentation and grain growth as a function of temperature, and type I or type II inward migration according to the embryo mass (§10.10.2), with typical migration times  $10^3 - 10^4$  yr.

As originally suggested by Boss, solid grains within the clump collide and grow and settle toward the centre forming a solid terrestrial-mass core. If the solid core becomes more massive than  $10M_{\oplus}$ , a massive gas atmosphere collapses on to the solid core. As the giant embryos migrate closer to the parent star, their Hill radius decreases faster than they can shrink due to internal cooling. At a few au from the star, tidal shear and evaporation due to stellar irradiation remove the clump's outer metal-poor envelope. If tidal disruption occurs before accretion of a massive gas envelope, a terrestrial planet core is left. If it happens subsequently, a metal-rich gas giant planet with a solid core remains.

Essentially, ‘tidal downsizing’ is a hybrid scenario: giant planet formation starts with dust sedimentation inside a self-gravitating gas clump, as in the gravitational instability model (Boss, 1998), but continues as in the core accretion model with accretion of a massive metal-rich gas envelope from within the giant embryo: solid cores left by embryo disruption in the protoplanetary disk may grow further, by accreting solid debris from the disk, while giant planets may accrete more gas (Nayakshin et al., 2014), and also migrate inwards (§10.10.2).

Population synthesis simulations (Nayakshin, 2015a,c,d; Nayakshin & Fletcher, 2015; Nayakshin, 2016, 2017b) suggest that the scenario can explain many features of the observed exoplanet population, including the abundance of super-Earths, occurrence statistics of close-in planets, and various metallicity correlations, as well as making specific predictions, such as the mass function and chemical composition of massive cores. Other simulations have argued that it cannot be the principal mode of planet formation other than for gas giants at large semi-major axes (Forgan & Rice, 2013; Forgan et al., 2018).

The model has also been invoked to explain the high-temperature processed materials observed in solar system comets through synthesis in the hot giant embryos (Nayakshin et al., 2011), debris disks around main-sequence stars as well as the solar system's Kuiper belt (Nayakshin & Cha, 2012), and the formation of gas giants at large separations (Nayakshin, 2017a).

In effect, the original version of the gravitational instability model, and some of the objections to it (such as photoionisation by a nearby OB star being required to form the ice giants), is being re-examined with the inclusion of advances made in models of core accretion.

**Example** As an illustrative example, the 2d hydrodynamic simulations of Zhu et al. (2012a) include continuous mass loading from an infalling envelope, and show that high infall rates beyond 50 au can lead to disk frag-

mentation (Figure 10.22). Type I inward migration of the resulting clumps, with continued disk accretion at  $10^{-3} - 10^{-1} M_{\text{J}} \text{ yr}^{-1}$ , continues until gap opening terminates migration, with some clumps tidally destroyed in the process. Situations where the massive clumps are not disrupted, and open gaps, may be relevant to the formation of close binary systems similar to Kepler-16.

**Observational signatures** Jang-Condell & Boss (2007) considered the observability of ongoing planet formation by gravitational instability by simulating scattered-light images of such a disk. Density structures at high disk altitudes, and photometric variations on time scales much shorter than the orbital period of the planet, may be observable by future extremely large telescopes. Direct imaging provides other constraints on the giant planet population formed at large separations, and more detectability estimates have been made for ALMA, and for the second-generation imaging instruments with extreme adaptive optics and high-performant coronagraphs, such as Gemini-GPI and VLT-SPHERE (e.g. Janson et al., 2012a; Dong et al., 2016b; Mayer et al., 2016). In the simulations by Zhu et al. (2012a), fragmentation clumps can be as large as 10 au, with  $L \sim 2 \times 10^{-3} L_{\odot}$ , in principle detectable with ALMA, but with a lifetime before dynamical collapse of only  $\sim 1000$  yr.

A cold matter clumping in the edge-on massive protoplanetary disk Gomez's Hamburger (GoHam), observed with VLT-VISIR, and 350 au from the host A star, has been suggested as a candidate for a young protoplanet being formed by gravitational instability (Berné et al., 2015). It might be representative of the precursors of massive planets observed around A stars, such as HR 8799 or  $\beta$  Pic.

**Algorithmic implementation** While some analytical models of disk instability have been presented (e.g. Rafikov, 2007; Clarke, 2009), most insights have come from numerical simulations (e.g. Helled et al., 2014, their Section 2.2.2).

Global models are mostly based either on grid-based finite-differences codes, including CHYMERA/BDNL (Boley et al., 2007), IUHG (Michael & Durisen, 2010), ORION (Kratte et al., 2010a), FARGO (Meru & Bate, 2012), (Paardekooper et al., 2011b), and EDTONS (Boss, 2012a); or on (mesh-free Lagrangian) 3d smoothed-particle hydrodynamics (SPH) codes, including GASOLINE (Mayer et al., 2007), DRAGON (Stamatellos & Whitworth, 2008), GADGET2 (Alexander et al., 2008), GADGET3 (Cha & Nayakshin, 2011), and SPH/MPI (Meru & Bate, 2010, 2012).

### 10.5.3 Comparison of the two mechanisms

The advantages, challenges, and complementarity of the core accretion and disk instability models are summarised in the review of Helled et al. (2014) as follows:

**Core accretion** The core accretion model can explain a number of features of the exoplanet population: (i) it can lead to the formation of both gas giants and ice giants; (ii) it can explain the correlations between stellar metallicity and giant planet occurrence, and between stellar and planetary metallicities; (iii) it is consistent with the enhancement of heavy element abundances in the solar system giants; (iv) it predicts that giant planets should be rare around stars with  $M_{\star} < M_{\odot}$ .

Challenges include: (i) it rests on the processes of planetesimal formation and early embryo growth which remain incompletely understood; (ii) the time scale for orbit decay due to type I migration remains short compared with the time required to build up the core to several  $M_{\oplus}$ ; (iii) it faces difficulties in explaining planets around stars of very low heavy-element abundance, or massive giant planets beyond  $\sim 20$  au; (iv) without migration, the formation time scale is close to the limits imposed by observations of protoplanetary disks; (v) final envelope abundances and formation time scales are dependent on the dynamics of planetesimals which remains uncertain; (vi) the uncertain opacity of the envelope plays a critical role in formation time scales.

**Disk instability** The main advantages of the disk instability mechanism are that: (i) fragmentation can lead to a variety of outcomes, including gas giants with and without cores, metal-rich and metal-poor gas giants, brown dwarfs, and possibly terrestrial planets. These various outcomes depend on the cooling, dust coagulation and settling, accretion, and migration time scales; (ii) planet formation can begin during the earliest stages of disk evolution; (iii) it may lead to many failed attempts at planet formation through fragmentation followed by tidal disruption, which could be linked with outburst activities of young protoplanetary disks, as well as to the processing of some of the first disk solids; (iv) it can take place at large disk radii and in low metal environments, consistent with systems such as HR 8799.

Its main challenges are that: (i) the conditions that lead to disk fragmentation, and the frequency of disks that become self-gravitating, are not well understood; (ii) even if protoplanets can be formed, whether they can survive tidal disruption and rapid inward migration to become gravitationally-bound planets is still questionable; (iii) it cannot easily explain intermediate-mass planets; (iv) it does not explain the correlation of giant planet occurrence and stellar metallicity.

**Complementarity** Core accretion and disk instability are not necessarily competing processes. Disk instability is likely most common during the early embedded phases of disk evolution (few  $10^5$  yr), while core accretion occurs at later stages (few Myr). In this view, disk instability could represent the first trials of planet formation, which may or may not be successful. If successful, it does not preclude formation by core accretion at later stages. Core accretion may be the dominant mechanism for ice giants and low-mass gas giants, while disk instability may be significant for the high end of the mass distribution, although both scenarios may lead to objects at both high and low masses.

## 10.6 Debris disks

**Introduction** The circumstellar disks observed in many older main sequence stars like the Sun (with ages from 10 Myr up to several Gyr) are believed to originate not from the gas and dust comprising the original protoplanetary disks (§10.2.2), but rather from gas-poor *debris disks*. The ‘debris’ is interpreted as a quasi-continuously generated by-product of the collisional attrition of planetesimals, asteroids and comets at the appropriate evolutionary stages of planet formation.

Evidence for this rests on a combination of the short dispersal time expected for the original gas disk ( $\sim 3$  Myr; §10.3.8), and their infrared spectral energy distributions (from which grain sizes, locations and compositions can be inferred), supported by numerical simulations of the planet formation and collisional processes.

Debris disks are often large, some extending to radial distances of 500 au or more, such as HD 15115 (Kalas et al., 2007) and 51 Oph (Stark et al., 2009). The surface area of the small disk particles being orders of magnitude larger than that of a planet, they emit and reflect light very well, and are particularly prominent at infrared wavelengths,  $2\ \mu\text{m}$ –1 mm (Beckwith, 1996). They display distinctive spectra much broader than any single-temperature black body, due to thermal emission over a wide temperature range, from  $\sim 1000$  K close to the star to  $\sim 10$ –30 K at the outer edges (Figure 10.23).

Hundreds of such debris disks are now known. The majority extend to radial distances of 50–100 au, and are ‘cold’. With advances in high angular resolution infrared observations from the ground and space, a number of ‘warm’ debris disks ( $\gtrsim 120$  K) have been found at much smaller radial distances of  $\lesssim 5$  au (§10.6.4).

In the solar system, analogous features are represented by the outer Kuiper belt dust disk beyond Neptune (§12.5.6) for the colder component, and the inner tenuous ‘zodiacal dust’, attributed to the slow but persistent collisions between asteroids, and manifested by the zodiacal light (§12.5.13) for the warmer component. In the young solar system, it is believed, such collisions were more common and the dust production rate likely to have been many times larger than today.

Although first detected through thermal emission of the dust, which creates an infrared excess in the spectral energy distribution of the otherwise normal stars that they surround, spatially-resolved debris disks are sometimes also visible from their scattered light.

Significant disk structure, and occasionally planets themselves, are now inferred or detected in many debris disks. These include rings, gaps, belts, clumps, eccentric and spiral patterns, and resonant structures attributed to (proto-)planets. The existence of debris disks provides evidence that the assembly of large bodies from  $\mu\text{m}$ -sized dust grains in protoplanetary disks builds up a planetesimal population comparable to that of the so-



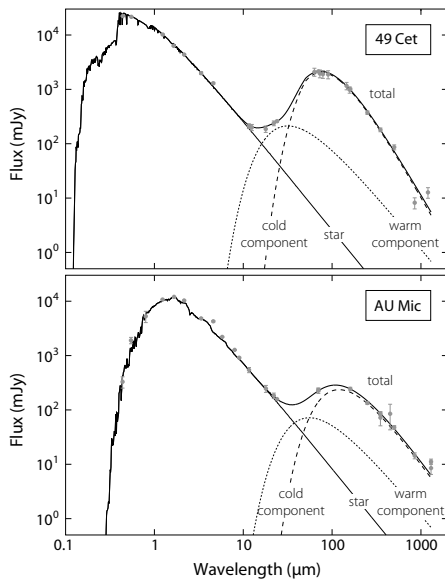


Figure 10.23: Example spectral energy distributions for the debris disk systems 49 Cet and AU Mic. Photometry is from various sources in the optical and near-infrared, with mid-infrared photometry from WISE, and far-infrared and sub-mm data from Herschel–PACS and SPIRE. Disks are modeled as modified black body fits to the sum of a warm (inner) and cold (outer) disk component in addition to the stellar flux. From Pawellek et al. (2014, Figure 1), by permission of IOP Publishing/AAS.

lar system’s asteroid and Kuiper belts, in environments which may also host larger planetary bodies.

Debris disks are inferred to evolve and in some cases persist or recur over several Gyr. They may undergo sporadic stirring and major collisional breakups, rendering them atypically luminous for brief periods. Observations have established occurrence statistics, and have stimulated advances in debris disk theory, providing new constraints on how planetary systems form and evolve. Various reviews provide further perspectives (e.g. Ozernoy et al., 2000; Kenyon & Bromley, 2002b; Reche et al., 2008; Stark & Kuchner, 2008; Wyatt, 2008; Raymond et al., 2011, 2012; Matthews et al., 2014b).

### 10.6.1 Discovery

Circumstellar debris disks were first identified through the infrared excess of  $\alpha$  Lyr (Vega), observed by the IRAS satellite. The absence of gas, and the star’s age, suggested that this was not simply a protoplanetary disk, but one arising from mm-sized particles at  $\sim 85$  au, heated by the star to  $T_{\text{eq}} \sim 85$  K, and ‘...providing the first direct evidence outside of the solar system for the growth of large particles from the residual of the pre-natal cloud of gas and dust’ (Aumann et al., 1984).

From IRAS, three other bright main sequence stars were found to exhibit a similar infrared excess: Fomalhaut,  $\epsilon$  Eri, and  $\beta$  Pic, together regarded as prototypes

of the ‘Vega-type’ phenomenon. Their ages range from  $\sim 10$  Myr ( $\beta$  Pic), 200–400 Myr (Vega and Fomalhaut), and up to  $\sim 1$  Gyr in the case of  $\epsilon$  Eri. Their disks are all extended and cold, with Vega at 86–200 au;  $\epsilon$  Eri at 35–75 au; Fomalhaut at 133–158 au; and  $\beta$  Pic at 25–550 au.

For older systems, classification as a transition or debris disk can be made according to details of the near-infrared excess (§10.3.8). However, with formational debris starting to appear at ages of a few 100 kyr, the youngest examples may be a combination of, or the transition between, the remnant protostellar disk and the secondary debris disk (e.g. Wahhaj et al., 2010).

**Observations** Probing the structure of debris disks benefits from high angular resolution imaging from optical to sub-mm wavelengths (§7.9). A number of systems are sufficiently nearby and bright for observations with the ‘second-generation’ optical imaging instruments operational since around 2016 (Gemini–GPI, VLT–SPHERE and Subaru–HiCIAO), with further diagnostics available from polarimetry. Observations have been made from the ground at infrared (Keck–NIRSPEC, VLT–MIDI, VLT–SINFONI, LBT–LMIRcam) and sub-mm wavelengths (ALMA, APEX–LABOCA, CARMA, IRAM–PdBI, JCMT–SCUBA2, SMA), as well as from space (Herschel–PACS, HST–STIS, ISO, Spitzer–MIPS, WISE). For example, the Spitzer IRS Debris Disk Catalogue assembles hundreds of debris disk candidates observed with Spitzer–IRS (Chen et al., 2014a; Mittal et al., 2015).

Interferometry, e.g. with CHARA–FLUOR and VLTI–PIONIER, has the potential to probe the innermost disk regions (Absil et al., 2013a; Ertel et al., 2014, 2016).

High sensitivity, high angular-resolution observations, notably with ALMA, have the potential to resolve structures and chemical signatures, including those induced by planet–disk interactions (e.g. Ertel et al., 2012b; Isella et al., 2012; Douglas et al., 2013; Ruge et al., 2014; Lieman–Sifry et al., 2016; Steele et al., 2016).

**Notable systems** The systems discovered with IRAS have since been characterised in considerable detail. More than a hundred others have since been resolved. Examples include:

- *Fomalhaut*: the debris disk, and inferred collisional processes, are well established and extensively observed, beginning with sub-mm observations of an asymmetric disk (Wyatt & Dent, 2002; Holland et al., 2003). Successive observations led to the prediction (Kalas et al., 2005; Quillen, 2006a), and eventual imaging (Kalas et al., 2008) of a candidate planetary body orbiting at 120 au (§7.10.2). The large orbit has been interpreted in the context of outward migration of a pair of planets (§10.10.2), leading to the prediction of a second planet at  $\sim 75$  au (Crida et al., 2009b). A detailed bibliography is given in Appendix F.
- *Vega*: the disk around Vega has been detected and further characterised in numerous studies (e.g. Wilner et al., 2002; Su et al., 2005; Defrère et al., 2011; Raymond & Bonsor, 2014; Janson et al., 2015, and references). Raymond & Bonsor (2014) attribute the hot dust disk to icy planetesimals scattered inwards by an outward-migrating planetary system.



• *c Eri*: is a main sequence star at  $d = 3$  pc, with a known planetary companion (*c Eri b*) detected by radial velocity (Hatzes et al., 2000) and astrometry (Benedict et al., 2006), and a well-resolved dust disk. Numerous observations of the disk have been reported, and a detailed chronology of discoveries and interpretation is given in Appendix C.

•  *$\beta$  Pic*: at a distance of 19.4 pc,  *$\beta$  Pic* has an age of  $\sim 10$  Myr (Smith & Terrile, 1984). The inner region is largely devoid of gas and dust, and ring-like structures are prominent. Studies have found comet-like bodies (Beust et al., 1994; Roberge et al., 2006b); effects of stellar encounters (Kalas et al., 2001; Larwood & Kalas, 2001); collisional debris (Beust & Morbidelli, 2000; Thébault & Beust, 2001; Karmann et al., 2003; Thébault et al., 2003; Okamoto et al., 2004; Telesco et al., 2005); and effects of an inferred planet (Lecavelier des Etangs et al., 1996, 1997; Galland et al., 2006a; Golimowski et al., 2006; Roberge et al., 2006a; Freistetter et al., 2007; Quillen et al., 2007). A candidate was duly suggested (Figure 10.24c), with  $a \sim 8$  au,  $M \sim 8M_J$ , and  $T \sim 1500$  K (Lagrange et al., 2009c,b; Lecavelier des Etangs & Vidal-Madjar, 2009; Fitzgerald et al., 2009). A detailed bibliography is given in Appendix F.

• *HD 100546*: the complex disk structure, with at least one embedded planet discovered from direct imaging, has an extensive observational history, also detailed in Appendix F. Observations with VLT-SPHERE show a complex azimuthal morphology, with ubiquitous high-brightness contrasts and arm-like structures, and in which multiple photon scattering most likely plays an important role (Garufi et al., 2016).

• *HD 141569*: at  $d \sim 100$  pc and with an age of 1–10 Myr, the disk possibly comprises both protostellar and debris dust extending to  $\sim 400$  au (Weinberger et al., 1999). A bright inner region is separated from a fainter outer region by a dark band, resembling Saturn's Cassini division (Figure 10.24a). An unseen planet may have carved out the gap at 250 au, in which case its properties can be estimated as  $M_p \sim 1.3M_J$ ,  $P \sim 2600$  yr. If it takes  $\sim 300$  periods to clear such material (Bryden et al., 1999) then the gap could be opened in  $\sim 8 \times 10^5$  yr, consistent with its age. There is an extensive literature on this object.

• *HR 4796A*: with an age of 8 Myr, HR 4796A has a prominent dust ring imaged in the infrared with HST-NICMOS (Figure 10.24b), and suggesting grain sizes of a few  $\mu\text{m}$  (Schneider et al., 1999). An extensive literature includes later observations with HST-STIS, Subaru-HiCIAO, Gemini-NICI, Gemini-GPI, and VLT-SPHERE. The most recent HST-STIS imaging also now reveals the exo-ring environment (Schneider et al., 2018).

• *HR 8799*: the system has a prominent debris disk associated with four known planets. The planets have been imaged, and their orbits followed and characterised (§7.10.2). A detailed bibliography is given in Appendix F.

**Other examples** Debris disks in many other evolved systems, with a qualitative similarity to the asteroid and Kuiper belts and zodiacal dust cloud in the solar system, are now known.

Several tens, out to more than 100 au, have been observed with Herschel-PACS, some as part of the 'DUNES' and 'DEBRIS' surveys (e.g. Donaldson et al., 2012; Ertel et al., 2012a; Löhne et al., 2012; Booth et al., 2013; Dent et al., 2013; Eiroa et al., 2013; Marshall et al., 2014; Pawellek et al., 2014; Moro-Martín et al., 2015; Dodson-Robinson et al., 2016; Vican et al., 2016). Eiroa et al. (2013) reported detections at a fractional luminosity level down to several times that of the Edgeworth-Kuiper belt, and with more than 50% spatially resolved. The incidence rate of disks around the DUNES sample increased from  $12 \pm 5\%$  pre-Herschel, to some  $20 \pm 2\%$ .

Surveys have also been conducted with the APEX-LABOCA sub-mm bolometer array (e.g. Nilsson et al., 2010); with the Caltech Submillimeter Observatory, SMO (Bulger et al., 2013); with JCMT-SCUBA2 between 2012–15, with the SONS survey finding evidence for disks in some 50% of 100 nearby stars (Panić et al., 2013; Holland et al., 2017); with Spitzer-MIPS (Geers et al., 2012; Sierchio et al., 2014); with HST-STIS coronagraphy (Schneider et al., 2014); and with WISE (e.g. Morales et al., 2012; Zuckerman et al., 2012; Kennedy & Wyatt, 2013; Patel et al., 2014, 2017).

A survey of 678 main sequence stars with AKARI yielded 8 new detections, a total of 53 debris disk candidates, and a detection rate of debris disks of 8% (Ishihara et al., 2017b).

From a complete sample of Hipparcos main sequence stars within 150 pc, and yielding 6 new warm dust candidates, Kennedy & Wyatt (2013) characterised the bright end of the exozodiacal luminosity function (box, page 342), finding that very old ( $>1$  Gyr) very dusty systems such as BD+20 307 (Song et al., 2005; Zuckerman et al., 2008) are very rare (1 in 10 000), while exozodiacal levels bright enough to be problematic for future exo-Earth imaging is at least 10%. Patel et al. (2014) identified 220 Hipparcos debris disk host stars within 75 pc. Sierchio et al. (2014) characterised a decline in occurrence between 3–4.5 Gyr.

Some other systems which have been observed in detail, or which include prominent structures, include (only a recent reference is given) HD 32297 (Rodigas et al., 2014a), HD 69830 (Tanner et al., 2015a), HD 95086 (De Rosa et al., 2016), HD 202628 (Thilliez & Maddison, 2016), HIP 73145 (Feldt et al., 2017), and  $\tau$  Cet (MacGregor et al., 2016a). These wide-ranging results are not detailed further here.

## 10.6.2 Occurrence

Various surveys and many other observations, from ground and space, have shown that debris disks are common around nearby young stars within 50–100 pc (Zuckerman, 2001; Trilling et al., 2008). Occurrence rates are  $\sim 30\%$  at ages of  $\sim 50$  Myr, falling to a few per cent at 100–1000 Myr (e.g. Laureijs et al., 2002; Mann et al., 2006; Su et al., 2006; Matthews et al., 2007; Siegler et al., 2007; Hillenbrand et al., 2008; Carpenter et al., 2009; Greaves et al., 2009; Moerchen et al., 2010; Dodson-Robinson et al., 2011; Eiroa et al., 2011; Millan-Gabet et al., 2011; Moór et al., 2011; Morales et al., 2012; Urban et al., 2012; Eiroa et al., 2013; Melis et al., 2013; Thureau et al., 2014).

From a Spitzer survey of the Hyades, Coma Ber, and Praesepe, combined with other literature values, Urban et al. (2012) derived rates at 670 Myr of  $8 \pm 3\%$  for B9–F4 stars, and  $3 \pm 2\%$  for F5–K9.

**Planetary systems with debris disks** Alongside more general surveys, searches for debris disks have been made around the host stars of known planetary systems, both from ground and space (e.g. Spitzer, Herschel, and WISE). Although not particularly common, incidence rates have risen as instrument sensitivity has improved (e.g. Greaves et al., 2004a; Saffe & Gómez, 2004; Schütz et al., 2004a; Beichman et al., 2005b; Faber & Quillen, 2007; Shankland et al., 2008; Kóspál et al., 2009; Quillen, 2010; Bonsor et al., 2013a, 2014a; Wittenmyer & Marshall, 2015; Dodson-Robinson et al., 2016).

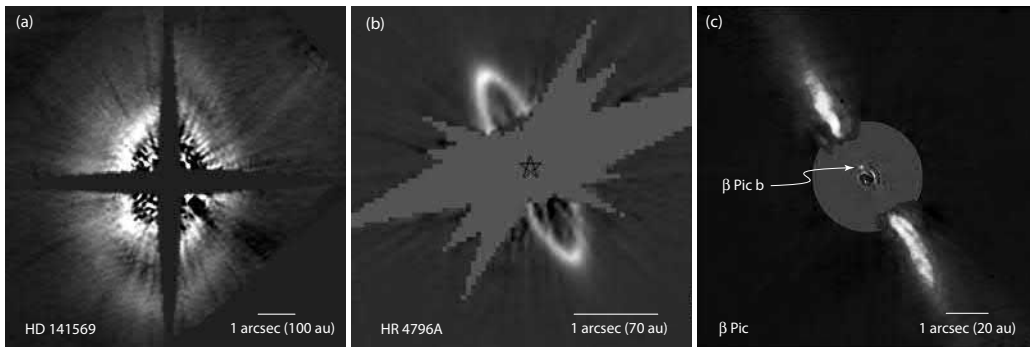


Figure 10.24: Examples of imaged debris disks: (a) HD 141569 observed at  $1.1\ \mu\text{m}$  with HST–NICMOS (Weinberger et al., 1999, Figure 1). (b) HR 4796A, observed in the optical with HST–STIS (Schneider et al., 2009a, Figure 2; this version courtesy G. Schneider). (c)  $\beta$  Pic, from combined ESO 3.6- $\mu\text{m}$  ADONIS imaging in 1996 (outer region), and  $3.6\ \mu\text{m}$  observations with VLT–NACO (inner region) revealing the probably planet,  $\beta$  Pic b (Lagrange et al., 2009b, this version courtesy A.M. Lagrange, D. Ehrenreich, and ESO). In all cases, the geometric central structures are artefacts of the coronagraphic imaging.

Spitzer–MIPS observations at 24 and  $70\ \mu\text{m}$  found debris disks around 10 of 150 surveyed stars with known planets (Beichman et al., 2005b; Kóspál et al., 2009).

For 591 known planetary systems, WISE observations at 12 and  $22\ \mu\text{m}$  found 9 showing excess dust emission, with 1% of all main-sequence stars showing evidence for planetary debris disks (Morales et al., 2012).

From the collective Herschel observations of 37 exoplanet hosts within 25 pc, Marshall et al. (2014) found 11 debris disks, with an incidence of  $29 \pm 9\%$  around solar-like hosts. They found a correlation between the increased presence of dust, lower planet masses, and lower stellar metallicities, confirming a suggested correlation between cold debris disks and low-mass planets (Maldonado et al., 2012; Wyatt et al., 2012).

Searches around 997 Kepler host stars with WISE found infrared excesses around only 8 solar-type stars, indicating warm to hot dust (100–500 K) at 0.1–10 au (Lawler & Gladman, 2012). A correlated search for 180 000 stars observed by Kepler and WISE confirms the low debris disk occurrence rate, while providing no evidence that the disk distribution around planet hosts is different from that of the bulk stellar population (Kennedy & Wyatt, 2012; Merín et al., 2014).

Multi-planet systems known to harbour debris disks include GJ 581 (Lestrade et al., 2012), HD 38529 (Moro-Martín et al., 2007), HD 69830 (Heng, 2011), HD 82943 (Kennedy et al., 2013), HD 100546 (Garufi et al., 2016), and HD 128311, HD 202206 and HR 8799 (Moro-Martín et al., 2010a). In the case of HD 82943, for example, observations suggest that the two planets, the stellar equator, and the dust disk, are all aligned (Kennedy et al., 2013).

**Debris disks with planets** Conversely, high contrast imaging searches for planets have been made in systems with ‘gapped’ debris disks, as inferred from their infrared

spectra. Meshkat et al. (2015) reported null results from their VLT–NACO coronagraphic  $L'$  search around six systems. Meshkat et al. (2017) reported null results from a search of 30 Spitzer-selected targets with Keck and VLT.

Simulations can be used to estimate the planet mass required to clear the observed gaps (Shannon et al., 2016a). Gaps can also be opened in dynamically cold debris disks at the mean motion resonances of an orbiting planet (Tabeshian & Wiegert, 2016, 2017). Such gaps, away from the planetary orbit, are large and deep enough to be resolved for a range of reasonable disk–planet parameters, their shape and size being a diagnostic of the planet location, eccentricity and mass.

**Young solar-type stars** At much younger ages than those of typical debris disk systems,  $\lesssim 10$  Myr, viz. during the epoch of terrestrial planet assembly, the incidence rate of warm debris disks around solar-type stars is much lower, at  $\lesssim 3\%$  (Kenyon et al., 2016). Being much lower than the  $\sim 20\%$  frequency of Earth-mass planets around older solar-type stars, Kenyon et al. (2016) suggested either that rocky planet formation occurs more quickly and/or more efficiently than generally believed, leaving behind little in the way of a dust signature, or that some previously-unrecognised mechanism (such as gas drag in a residual gaseous disk) removes warm dust efficiently from the terrestrial planet region.

**M dwarfs** The occurrence of debris disks around M dwarfs probes formation and evolutionary processes over lower disk masses (e.g. Heng & Malik, 2013). Spatially-resolved disks were first identified around the young (12 Myr) star AU Mic (e.g. Kalas et al., 2004; Schneider & Schmitt, 2010; Wilner et al., 2012; Matthews et al., 2015; Schüppler et al., 2015; Wang et al., 2015e; Chiang & Fung, 2017), and the much older (2–8 Gyr) GJ 581, extending radially from 25–60 au (Lestrade et al., 2012).

Avenhaus et al. (2012) reported a null detection rate in their search for debris disks in a sample of 85 M stars using data from WISE, in contrast to their prevalence around A, F and G stars (e.g. Urban et al., 2012, and references). Models by Heng & Malik (2013) suggest that the apparent dearth of M star debris disks can be explained by a combination of the dust’s black body spectrum combined with the small semi-major axes probed.

**Neutron stars and white dwarfs** At least one, cool  $10M_{\oplus}$ , debris disk has been identified around the young X-ray pulsar 4U 0142+61 (Wang et al., 2006). These are relevant in the context of a possible formation pathway for the planet-mass objects found around pulsars (§4.2.2), although not necessarily formed by collisional attrition. The broad topic of debris disks around white dwarfs is discussed in Section 8.9.

**Thick disk stars** A Spitzer–MIPS survey of 11 of the closest thick disk stars failed to detect dust in any (Sheehan et al., 2010). Although some stars of this very old population do host giant planets, the data rule out a high incidence of debris among star systems from early in the Galaxy’s formation.

**Signatures at high redshift** A dust-budget ‘crisis’ in galaxies was elucidated by Morgan & Edmunds (2003), who argued that dust from stellar winds of low/intermediate mass stars, believed to be the dominant source of stardust in galaxies (Whittem, 2003), failed to explain the quantities seen in high-redshift galaxies ( $z \sim 5$ ). Since then, substantial dusty reservoirs discovered at  $z \sim 6 - 7$  with Herschel (Riechers et al., 2013) and ALMA (e.g. Watson et al., 2015; Willott et al., 2015; Knudsen et al., 2017) place more stringent constraints, requiring significant dust production on time scales of only a few 100 Myr (Gall et al., 2011; Mattsson et al., 2014; Mancini et al., 2015c; Michałowski, 2015).

Forgan et al. (2017) suggested that the apparent underproduction of dust mass in high-redshift galaxies by chemical evolution models could be, in part, due to neglecting the process of planet formation with its attendant dust production (via grain growth in protostellar disks, and via the grinding of larger bodies in debris disk systems). They suggest that this can partially improve the dust budget deficit under specific conditions of dust reprocessing.

### 10.6.3 Dust modeling

Through the absorption, emission, and scattering of radiation, dust grains provide diagnostics of the local density and temperature structures. While other texts should be consulted for details (e.g. Bohren & Huffman, 1983; Draine, 2003; Steinacker et al., 2013), the following points are particularly relevant for debris disks.

Scattering is a strong function of grain size, while the minimum particle size (which dominates the scattering cross section) is a function of stellar radiation pressure and therefore stellar luminosity (e.g. Mittal et al., 2015; Pawellek & Krivov, 2015). Initial dust masses are correlated with host star metallicity (Gáspár et al., 2016).

Scattering efficiencies decline beyond  $2 \mu\text{m}$  for sub-micron grains, although larger  $\mu\text{m}$ -sized grains can elevate scattered light intensities through the phenomena termed ‘cloudshine’ (Foster & Goodman, 2006) and ‘coreshine’ (Steinacker et al., 2010, 2015).

Surface reactions contribute to chemical processes in the gas, with available area depending on grain size and fractal dimension (§10.4.2). Grains are also sensitive to magnetic forces as a result of their charge and composition (Lazarian, 2007). Compositional insight is also accessible from infrared spectroscopy, e.g. with silicates identified in disks such as BD+20 307 (Song et al., 2005) and 51 Oph (Stark et al., 2009).

**N-body simulations** Detailed numerical modeling aims to understand the origin of the observed debris disk structures, such as bright clumps, azimuthal asymmetries, spiral arms, warps, and eccentricities.

In many cases, scenarios invoke a perturbing planet, for instance for the warp of the  $\beta$  Pic disk (Mouillet et al., 1997; Augereau et al., 2001), brightness asymmetries in  $\epsilon$  Eri (Kuchner & Holman, 2003), the confined rings around HR 4796A and Fomalhaut (Wyatt et al., 1999; Kalas et al., 2005; Chiang et al., 2009), and eccentric disk structures, for example in  $\zeta^2$  Ret (Faramaz et al., 2014; Pan et al., 2016; Saffe et al., 2016).

Other effects modeled include stellar perturbations (e.g. Augereau & Papaloizou, 2004; Thébault et al., 2010); gas interactions (Takeuchi & Artymowicz, 2001; Besla & Wu, 2007); interactions with the interstellar medium (Artymowicz & Clampin, 1997; Debes et al., 2009; Marzari & Thébault, 2011; Stark et al., 2014b); transient violent events (Kenyon & Bromley, 2005; Grigorieva et al., 2007; Stark et al., 2014b), the effect of dwarf planets on the eccentricities and inclinations of disk particles (Muñoz-Gutiérrez et al., 2017), and the influence of dust grain porosity (Brunngräber et al., 2017).

Numerical exploration of these different scenarios has mostly been made using collisionless N-body codes, which follow the development of dynamical structures such as resonances and migrations (e.g. Kuchner & Holman, 2003; Reche et al., 2009).

**Binary stars** Disks, both protoplanetary and debris, provide further insights into planet formation. Specific simulations of debris disks in binary star systems have been reported (Thébaud et al., 2010; Thébaud, 2012; Rawiraswattana et al., 2016). Amongst the findings, Thébaud et al. (2010) showed that a companion star can never fully truncate a collisionally-active disk.

Constraints on protoplanetary disk alignments are rather limited; protoplanetary disks in a few young binaries are known to be misaligned with respect to the binary orbital plane, with HK Tau, at  $\sim 65^\circ$ , being a particularly pronounced example (Jensen & Akeson, 2014).

Debris disks accompanying binary or multiple stars are common. The Spitzer study by Trilling et al. (2007) found that debris disks are generally as common in binary systems as in single systems, but are less likely in systems with binary separations of 3–30 au. The Herschel DEBRIS programme found that 188 out of the 449 systems observed (42%), covering spectral types A–M, were binary or multiple (Rodríguez et al., 2015). Further modeling is reported by García & Gómez (2016).

There are a few such systems which have both spatially-resolved disks and well-characterised binary orbits, notably HD 98800 (Andrews et al., 2010), 99 Her (Kennedy et al., 2012a), and  $\alpha$  CrB and  $\beta$  Tri (Kennedy et al., 2012b). The combination provides robust conclusions about whether the dust resides on stable orbits, as

well as a comparison of their relative inclination. From these systems, Kennedy et al. (2012b) has suggested an emerging picture in which disks around very close binaries with periods of a few weeks to a year ( $\alpha$  CrB,  $\beta$  Tri, and HD 98800) are aligned, while disks around wider binaries (e.g. 99 Her,  $P \sim 50$  yr) are misaligned.

**Collisional evolution** The collisional evolution of debris disks is usually studied separately from structural models using N-body simulations. The focus is on properties such as grain-size distributions and mass loss.

The general picture of debris disks is one of dust emission sustained by the fragmentation of colliding planetesimals, possibly stirred by forming planets. The process continues until bodies are ground down to  $\mu\text{m}$ -sized dust, when sub- $\mu\text{m}$ -sized particles are ejected by radiation pressure, while 1–100  $\mu\text{m}$ -sized particles spiral into the star on time scales of  $10^3 - 10^4$  yr due to Poynting–Robertson drag. Debris disks presumably consist of bodies spanning a wide size range, from 1–100 km-sized planetesimals down to micron-sized dust. However, dominating the geometrical cross section, it is only the smaller particles of the collisional cascade ( $\leq 0.01$  m) that are detectable, both in thermal emission and in scattered light.

The spectral energy distribution provides constraints on the radial distance of the planetesimal belt, and collisional models can be used to reproduce the observed spectral energy distributions and determine the detailed disk parameters, including total mass, grain size, and scattering properties (e.g. Krivov et al., 2007, 2008; Edgar & Quillen, 2008; Wyatt, 2008; Greaves, 2010; Hahn, 2010; Kalas, 2010; Sinclair et al., 2010; Guilloteau et al., 2011; Kennedy & Wyatt, 2011; Shannon & Wu, 2011; Wolff et al., 2011; Thébault et al., 2012; Zuckerman et al., 2012; Kennedy & Wyatt, 2014; Kobayashi & Löhne, 2014; Pearce & Wyatt, 2014; Schüppler et al., 2014; Leinhardt et al., 2015; Dobinson et al., 2016; MacGregor et al., 2016b; Thébault, 2016; Kenyon & Bromley, 2017c).

The total mass within debris disks, as well as their infrared excess, was originally estimated assuming a mass distribution following that of the asteroid belt, which predicted that sizes would follow a power law of the form  $n(a) \propto a^{-3.5}$  (Dohnanyi, 1969), as also inferred for the interstellar medium (Mathis et al., 1977). Subsequent observational fits have generally found similar or slightly steeper slopes (e.g. Krist et al., 2010; Golimowski et al., 2011; Greaves et al., 2012), with more recent collisional-cascade models also finding  $\sim 3.60$ – $3.65$  (e.g. Thébault et al., 2003; Krivov et al., 2005; Thébault & Augereau, 2007; Löhne et al., 2008; Müller et al., 2010; Wyatt et al., 2011; Gáspár et al., 2012b, 2013). The slope is related to the tensile strength curve, i.e., to the minimum energy required for catastrophic disruption (Durda & Dermott, 1997; Benz & Asphaug, 1999; Holsapple et al., 2002; O’Brien & Greenberg, 2003; Gáspár et al., 2012a).

**Second-generation gas** In addition to primordial residual gas seen in some systems, a growing number of gas detections in dusty debris disks (notably CO, C, and O) are being made. Attributed to second-generation gas arising from the attrition of icy planetesimals, the general picture is that of CO being produced from volatile-rich solid bodies at a rate that can be predicted from the debris disk’s fractional luminosity (Kral et al., 2016, 2017). CO then photodissociates rapidly into C and O, which then evolve by viscous spreading. The model provides a qualitative explanation of current observations, and predicts some 15 CO detections and some 30 C I detections with ALMA (e.g. Marino et al., 2017b), and tens of C II and O I detections with future far-infrared missions.

**Combined models** Including destructive collisions into an N-body scheme is computationally expensive. It can be tackled by breaking bodies into fragments whose evolution is then followed dynamically, a scheme constrained by number of particles that can be followed (Beauge & Aarseth, 1990). An alternative is to ‘post-process’ collisionless N-body simulations assuming that each test particle represents a dust-producing collisional cascade, an approach allowing exploration of time scales up to several Gyr (Booth et al., 2009).

Further algorithmic developments include ACE (Löhne et al., 2017); CGA (Stark & Kuchner, 2009); DyCoSS (Thébault, 2012); EDACM (Leinhardt et al., 2015); LIPAD (Levison et al., 2012; Kretke & Levison, 2014); REBOUND (Rein & Liu, 2012); and SMACK (Nesvold et al., 2013; Nesvold & Kuchner, 2015a).

More closely coupling the collisional and dynamical evolution of a debris disk over a few orbital periods, Grigorieva et al. (2007) adopted an approach in which each particle of an N-body simulation is a ‘tracer’ (or ‘super-particle’) representing a larger population of particles of a given size, with the code tracking mutual collisions between tracers. Collisions are treated with a classical particle-in-a-box approach, estimating the mass lost by the impacting tracers, with the corresponding mass injected into new tracers that carry the collisional fragments. LIDT-DD exploits a similar tracer approach, coupling dynamical and collisional evolution (along with radiation pressure), and adapting the tracer to the specific requirements in any given region of the disk (Kral et al., 2013, 2015).

**Hydrodynamical effects** For debris disks with significant gas content, hydrodynamical models indicate that dust–gas interactions can produce some of the features previously attributed to planets (Lyra & Kuchner, 2013; Birnstiel & Andrews, 2014; Hughes et al., 2017). Lyra & Kuchner (2013) found a clumping instability that organises the dust into narrow eccentric rings, as in Fomalhaut, and concluded that embedded planets are not required to explain at least some observed structures.

**Dynamical state** Heng & Tremaine (2010) classified debris disks as *dynamically hot* (or ‘cold’) depending on whether the planetesimal orbits cross (or not); within the solar system, the planets (excluding Pluto) form a cold system, while the asteroid and Kuiper belts are hot. *Collision-limited* (hot) disks, in which the collision time between planetesimals is equal to the age of the disk, arise from disks with a range of planetesimal sizes: smaller planetesimals have shorter collision times and therefore are destroyed first, such that the dominant planetesimal population (by mass) always has a collision time roughly equal to the disk age. In dynamically *warm disks*, the planetesimal orbits cross, but the impact velocities are sufficiently low that collisional damage is limited.

#### 10.6.4 Other manifestations

**Warm debris disk systems** While most known debris disks comprise cold dust at a few tens of au, and are considered as massive analogues of the Kuiper belt well replicated by collisional cascade models, a small number exhibit inner ( $\lesssim 5$  au) warm dust analogous to the zodiacal dust, or a two-component structure, with an outer cold Kuiper belt analogue and a warm inner component. Examples include BD+20 307 (Song et al., 2005), HD 12039 (Hines et al., 2006), HD 98800 (Furlan et al., 2007), HD 69830 (Lisse et al., 2007),  $\zeta$  Lep (Moerchen et al., 2007), and  $\eta$  Crv (Marino et al., 2017b).

The origin of these warm inner disk components remains uncertain (e.g. Schüppler et al., 2016; Ballering et al., 2017; Geiler & Krivov, 2017; Marino et al., 2017b). The majority of disks with warm dust are younger than  $\sim 100$  Myr (Kennedy & Wyatt, 2013), while the regularity of the disk temperatures indicates an underlying structure linked to the H<sub>2</sub>O-snow line (Ballering et al., 2017).

Surveys of debris disks (§10.6.2) have shown that the levels of infrared excess decay with stellar age, as expected from collisional models. Since collisional timescales are a steep function of radial distance (Löhne et al., 2008), debris disks at a few au are expected to evolve much faster than the Kuiper belt analogues at a few tens of au. This implies that there is a maximum possible disk mass at a given radius and age, and thus a maximum dust luminosity (Wyatt et al., 2007c; Löhne et al., 2008).

However, a subset of disks with warm/hot dust around old ( $\gg 100$  Myr) stars exceed this limit by a factor  $10^3$  or more, ruling out its explanation as a result of steady-state destructive collisions between planetesimals *in situ* (Wyatt et al., 2007b). Warm dust in these systems must either be replenished from cometary sources farther from the star, where collisions are less frequent and the disk mass decays more slowly, or represent an aftermath of a recent rare event, such as a major collision or planetary system instability.

**$\eta$  Crv** As an example, the 1–2 Gyr F2V star  $\eta$  Crv hosts both hot ( $\sim 1$  au) and cold ( $\sim 150$  au) dust components, with its hot dust significantly exceeding the maximum luminosity of an *in situ* collisional cascade. Explanations for the hot dust (Marino et al., 2017b) include: (1) an ongoing instability, analogous to the Late Heavy Bombardment in the solar system (box, page 669), scattering comets from the outer belt to the inner regions; (2) planets scattering dust from the outer disk feeding the hot dust or bigger icy solids that then collide closer in producing the hot dust; (3) planetesimals scattered by planets, colliding with a planet within a few au, and releasing large amounts of debris.

**Old debris disk systems** The significant debris disks in some older systems, with ages 100 Myr–1 Gyr, require some adjustments to models invoking steady-state collisional attrition. Some (e.g. Bonsor et al., 2013b) may result from a delayed cometary flux, analogous to the solar system’s Late Heavy Bombardment (§12.6.3), due to a dynamical instability attributable to planetary re-arrangement along the lines of the Nice model (§12.6). Again, such events may have taken place in  $\eta$  Crv, which has too much hot dust to be explained by collisional evolution alone (Booth et al., 2009; Lisse et al., 2012).

Dust levels could perhaps be maintained throughout the lifetime of some older systems through planetesimal scattering by chains of tightly packed low-mass planets (Bonsor et al., 2012, 2014b; Raymond & Bonsor, 2014). Mean motion resonances with exterior planets on moderately eccentric orbits ( $e \gtrsim 0.1$ ) can also scatter planetesimals into cometary orbits, possibly sustaining the continuous production of active comets over Gyr time scales (Faramaz et al., 2015, 2017).

Replenishment through Lidov–Kozai excitation of the particles’ eccentricities and inclinations has also been considered (Nesvold et al., 2016).

Predictions of the occurrence and (limited) detectability of debris disks around giant stars has been made by Bonsor & Wyatt (2010). Herschel results for subgiants are reported by Bonsor et al. (2014a).

**Variability and giant impacts** Collisional-cascade models tend to solutions in which rapid infrared variations are not expected. However, in the age range 30–130 Myr, a few *extreme debris disks* show infrared excess and mid-infrared spectra suggesting that giant impacts have occurred recently. Some also show large variations over several years, including TYC 8241–2652–1 (Melis et al., 2012), 2M J0809–48 (ID8) in NGC 2547 and HD 23514 in the Pleiades (Meng et al., 2012).

In this age range, well-separated from that of protoplanetary disks, models predict that giant impacts will occur (§10.4.5). Analogous to the Moon-forming impact (§12.3.3), such events should yield substantial heated debris and an infrared excess far above that of quiescently evolving systems (e.g. Balog et al., 2009; Jackson et al., 2014; Genda et al., 2015; Kral et al., 2015; Kenyon & Bromley, 2016b; Wyatt & Jackson, 2016).

In BD+20 307, for example, the quantity of dust inferred translates into a collisional grinding time scale of a few hundred years (Kenyon & Bromley, 2005), and Song et al. (2005) argue that a recently pulverised 300-km size asteroid is needed to account for infrared excess.

Strong variability may arise from Si-rich vapour associated with extended episodes of violent collisions, possibly triggered by a single event (Meng et al., 2012). Laboratory experiments suggest that the vapour will condense quickly into silica ‘smoke’ (Kimura & Nuth, 2007; Visscher & Fegley, 2013), with forsterite ( $\text{Mg}_2\text{SiO}_4$ ) the most common crystalline form (Kobatake et al., 2008). Meng et al. (2015) monitored six extreme debris disk systems with Spitzer during 2015–16 and detected significant variations over 1 yr time scales in five, including long-term decay or growth, and possible periodicity.

From a large scale survey of low-mass field stars with SDSS, 2MASS, and WISE photometry, Theissen & West (2017) identified 583 exhibiting extreme mid-infrared excess. Their models are consistent with the excesses originating from dust created in a short-lived collisional cascade ( $\lesssim 10^5$  yr) during a giant impact between two large planetesimals or terrestrial planets.

Also attributed to a planetary-scale hypervelocity impact, but photometrically stable in the infrared over 30 yr, is the circumstellar disk at 6 au around the 12 Myr HD 172555 (e.g. Lisse et al., 2009; Johnson et al., 2012a; Kiefer et al., 2014a; Wilson et al., 2016b).

Detectability of planetesimal impacts on giant planets has been assessed using the 1994 comet Shoemaker–Levy 9 impact with Jupiter as proxy (Flagg et al., 2016). Sunlight normally absorbed by atmospheric  $\text{CH}_4$  was reflected by the cometary impact material, leading to substantial brightening at  $2.3 \mu\text{m}$  for more than a month.

**Transfer during stellar encounters** Debris disk matter can be transferred to another star during close fly-bys, with an efficiency which decreases with increasing encounter pericentre and increasing mass of the original disk host (Jílková et al., 2016). Many stars are likely to have experienced such transfers in their birth environment, a possible formation channel for objects on wide orbits, of arbitrary inclinations, and typically high eccentricity, and often distinct from planets formed directly around the star.

## 10.7 Formation of specific planet classes

Having examined the various mechanisms and phenomena believed to affect planetary formation and evolution, this section summarises the present understanding of the formation of various classes of planet.

### 10.7.1 Hot Jupiters

This section covers the processes which are believed to govern the formation and evolution hot Jupiters. Other

sections cover a summary of their overall occurrence rates in radial velocity and transit surveys (§1.6.2), the occurrence rates in radial velocity surveys (§2.11.4), and their discovery and associated properties from transit observations, including their inflated radii (§6.28). A broader treatment of Lidov–Kozai oscillations, which may be responsible for at least part of the hot Jupiter population, is given in Section 10.10.6.

**In situ versus ex situ formation** It is generally held that *in situ* formation of hot Jupiters is unlikely: in models of core accretion, both the available disk mass and the opening of disk gaps appear to preclude their growth (e.g. Rafikov, 2006), while in models of direct gravitational collapse due to disk instability, the gas cools too slowly for the spiral arms to fragment into bound clumps (e.g. Matzner & Levin, 2005; Rafikov, 2005). These considerations support the idea that hot Jupiters, or their massive progenitor cores, arrived at their present locations from their region of formation beyond the snow line ( $a \gtrsim 3$  au), where solid material is abundant due to condensation of ice (§11.2.3).

Assuming formation at much larger distances from the host star, there are then two favoured hypotheses to explain how they arrived at their presently observed locations: (i) inward disk-driven migration, or (ii) through the generation of a highly eccentric orbit with small pericentre, followed of tidal circularisation. There are several mechanisms which have been suggested to generate such high-eccentricity orbits.

**Inward migration** Inward orbital migration due to gravitational interactions with gas disks (§10.10.2) or planetesimal disks (§10.10.3) would naturally bring planets inward from their formation sites. Damping associated with disk migration can also account for the small eccentricities and obliquities seen in many of the close-in planets (Rice et al., 2012). Some kind of ‘halting mechanism’ must be invoked to prevent the inward migrating planet from falling terminally onto the host star (§10.10.2). Different populations of protoplanetary disks may have resulted in very different inward migration rates, with Jin (2010) suggesting that hot Jupiters would not be found around stars below  $0.14 - 0.28 M_\odot$ .

The spin–orbit alignments observed in multi-planet systems, such as Kepler–30 and Kepler–89, suggests that planets in at least these multiple transiting system have experienced a quiescent migration process rather than having been carried to the present locations by dynamical scattering processes or long-term perturbations by outer objects.

A very different proposed formation mechanism (with subsequent tidal dissipation) is in the massive compact disk formed in a merger event of two low-mass stars (Martin et al., 2011; Stepień & Kiraga, 2013), perhaps as in the case of V1309 Sco (Nandez et al., 2014).

Formation of gas giant progenitors in clumps via gravitational instability in protoplanetary disks has also been suggested (Galvagni & Mayer, 2014).

**Circularisation of eccentric orbits** Planets may also be brought into close-in orbits by first imparting them with a high eccentricity, followed by tidal damping during close pericentre passages resulting in orbital circularisation. The favoured candidates for imparting high eccentricities are planet–planet scattering (§10.10.4) and, given the presence of a distant hierarchical stellar binary companion, Lidov–Kozai cycles (§10.10.6).

High eccentricities may also arise from stellar encounters, perhaps in a young star cluster (de la Fuente Marcos & de La Fuente Marcos, 1997; Laughlin & Adams, 1998; Malmberg & Davies, 2009), or in the cores of globular clusters (Hammers & Tremaine, 2017). Malmberg & Davies (2009) found that their simulations result in an eccentricity distribution similar to that observed in the range of separation  $1 \lesssim a \lesssim 6$  au.

Shara et al. (2016) used N-body simulations to follow the fates of 100 systems, each comprising two Jupiter planets, in moderately dense open clusters with 18 000 single stars and 2000 binaries. Interactions with passing stars lead, in  $\lesssim 1$  Gyr, to strong interactions between the two planets, resulting in 3 (very) hot Jupiters (accompanied by much more distant gas giants in highly eccentric orbits) with orbits that mimic those of the most extreme semi-major axes and eccentricities known, such as HD 80606 b, GJ 876 d, HAT-P-2 b, HAT-P-32 b.

These gravitational interactions also tend to increase the orbital inclination, and indeed many hot Jupiters are found to have high stellar obliquities, i.e., large misalignment angles between the spin axis of the host star and the planetary orbital angular momentum axis. This indicates that, at a minimum, a significant number of hot Jupiters are formed through high-eccentricity channels.

For example, Chatterjee et al. (2008) performed a number of dynamical simulations of three-planet systems, and showed that the final mean inclination of planetary orbits is about  $i \approx 20^\circ$ , and that some planets could end up on retrograde orbits. Results from models of Kozai cycles are noted in Section 10.10.6.

Once the high eccentricity has been imparted, the subsequent step of tidal circularisation as a result of close pericentre passage is detailed further in these respective summaries. A tentative correlation between dispersion in spin–orbit angle and age suggests that systems may re-align within  $\sim 2.5$  Gyr, implying that hot Jupiters are placed on non-coplanar orbits early in their history (Triaud, 2011).

So far, observations of eccentricities and spin–orbit misalignments of hot Jupiter systems have been unable to differentiate between the various hypotheses. Models appear to rule out *all* known hot Jupiters as arising from Lidov–Kozai cycles with tidal friction, and it seems

likely that the observed systems have originated through a combination of these processes.

Spin–orbit misalignments tend to be seen only for ‘isolated’ hot Jupiters, suggesting that these may have (partly) migrated by more chaotic processes.

Chemical abundances may provide other constraints on the migration mechanisms, with sub-solar C and O abundances harder to explain as a result of disk migration (Madhusudhan et al., 2014a).

**Sub-Jovian desert** A general feature in the  $P_{\text{orb}} - M_{\text{p}}$  plane is a nearly empty area, outlined roughly by two oppositely sloped lines, in the region of sub-Jupiter-mass planets on short-period orbits (Szabó & Kiss, 2011; Beaugé & Nesvorný, 2013; Mazej et al., 2016). Matsakos & Königl (2016) showed that this feature, the ‘sub-Jovian desert’ (considered further in §6.27), can also be interpreted in terms of high-eccentricity migration, with the two distinct segments of the desert’s boundary reflecting the different slopes of the empirical mass–radius relation for small and large planets (e.g. Weiss et al., 2013). A plausible physical origin for the boundary is the Roche radius (Equation 6.82), the distance from the star where the planet starts to be tidally disrupted.

High-mass planets arriving by high-eccentricity migration, and crossing the Roche radius, lose their gaseous envelopes through tidal disruption, resulting in a natural inner edge to the observed distribution, corresponding to the boundary of the sub-Jovian desert (Königl et al., 2017). This edge generally lies interior to the predicted location of the circularisation (Giacalone et al., 2017). The remnant rocky cores can plausibly account for the population of dynamically isolated hot Earths (Steffen & Coughlin, 2016; Giacalone et al., 2017; Königl et al., 2017).

If close-in planets form by high-eccentricity migration, in which they reach the vicinity of the central star on high-eccentricity orbits that become circularised (as opposed to drifting inwards through the protoplanetary disk on nearly circular orbits), there should exist an eccentricity gradient with  $a$  near the location where the circularisation time becomes comparable to the planet’s age (for typical parameters). Studies have found evidence for this gradient, demonstrated that its properties are consistent with the circularisation process being dominated by tidal dissipation in the planet, and found evidence for a similar gradient in lower-mass planets, indicating that formation through high-eccentricity migration may be relevant down to Neptune scales (Pont et al., 2011b; Husnoo et al., 2012; Bonomo et al., 2017a; Giacalone et al., 2017).

### 10.7.2 Hot Neptunes to Earths

As observations have improved, close-in planets of progressively lower mass have been discovered. Early discoveries in the hot Neptune-class ( $10 - 20M_{\oplus}$ ) included

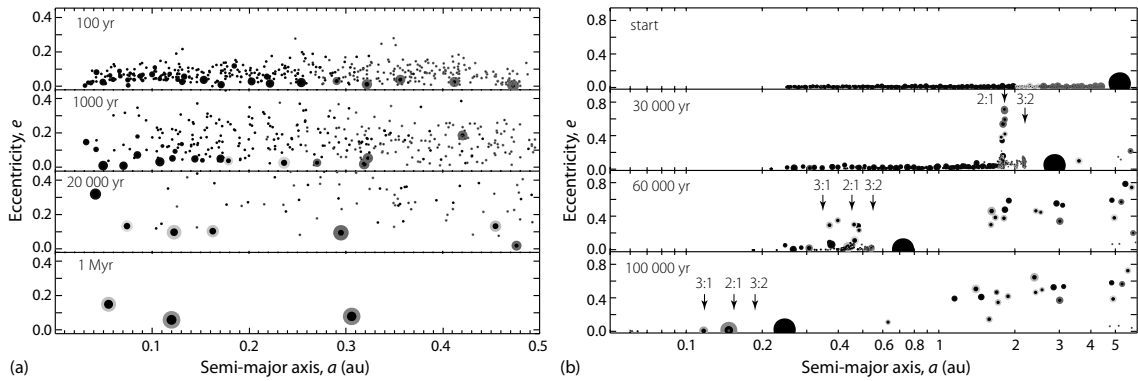


Figure 10.25: Two of a number of different formation models for hot Neptunes: (a) *in situ* accretion of a system of hot Earths. Object sizes are proportional to  $M^{1/3}$ . The dark circle in the centre of each body refers to the relative size of its iron core. The central star is  $0.31M_{\odot}$ , replicating GJ 581. The simulation started from a disk of 57 planetary embryos (initially separated by 3–6 Hill radii) and 500 planetesimals in a massive disk totaling  $40M_{\oplus}$  between 0.03–0.5 au; (b) the migration of a  $1M_J$  giant through a disk of terrestrial bodies. Specific strong resonances with the giant planet are indicated. Colour coding in the original figures corresponds to the body’s expected water content. From Raymond et al. (2008c, Figures 1–2), © Oxford University Press.

GJ 436 b (Butler et al., 2004b), HAT-P-11 b (Bakos et al., 2010), and the three-Neptune analogue HD 69830 (Lovis et al., 2006; Alibert et al., 2006).

These, along with the lower mass hot super-Earths and hot Earths ( $1 - 10M_{\oplus}$ ), may be a more common by-product of planet formation, following the canonical oligarchic picture of core accretion in a standard nebular environment, with type I migration.

Unlike the more massive hot Jupiters (where migration, planet–planet scattering, and Kozai cycles are considered as likely formation processes), a number of plausible origins for the lower-mass objects have been proposed (Zhou et al., 2005; Brunini & Cionco, 2005; Alibert et al., 2006; Gaidos et al., 2007; Kennedy & Kenyon, 2008a; Raymond et al., 2008c; Marcus et al., 2009; McNeil & Nelson, 2010; Nayakshin, 2011b; Boué et al., 2012a; Howe et al., 2014; Lopez & Fortney, 2014; Valsecchi et al., 2014; Morbidelli & Raymond, 2016).

Raymond et al. (2008c) provide a synopsis of these different models (Figure 10.25), and include the expected system architecture [indicated  $\Rightarrow$  in the following], along with the inferred planet composition, together perhaps providing sufficient diagnostics to distinguish between them. They are:

- (1) *in situ* accretion [ $\Rightarrow$  several hot Earths, spaced by 20–60 mutual Hill radii; box, page 512];
- (2) formation at larger orbital radii followed by inward type I migration [ $\Rightarrow$  a chain of many terrestrial planets, close to mutual mean motion resonances];
- (3) formation from material shepherded inward by a migrating gas giant [ $\Rightarrow$  co-existence of hot Earths and close-in giants near to strong mean motion resonances];
- (4) formation from material shepherded by moving secular resonances during disk dispersal [ $\Rightarrow$  a co-existence of hot Earths and at least two interacting giants];

(5) tidal circularisation of eccentric planets with small pericentres [ $\Rightarrow$  a single hot Earth, with possible distant companion to explain high eccentricity];

(6) mass-loss of a close-in gas or ice giant by photo-evaporation or collisional stripping [ $\Rightarrow$  a hot Earth inside 0.025–0.05 au, and a likely chain of several planets].

### 10.7.3 Super-Earths

**Properties** Super-Earth planets are a particularly abundant class, which have also posed a particular challenge for planetary formation models at both ends of the mass spectrum. Following the definition proposed by Morbidelli & Raymond (2016, see also §1.6.1), roughly half of all Sun-like stars appear to possess one or more planets with  $R = 1 - 4R_{\oplus}$  and  $P \leq 100$  d (Mayor et al., 2011; Howard et al., 2012b; Fressin et al., 2013; Haghighipour, 2013; Petigura et al., 2013b).

Being easier to detect than an Earth-sized planet at 1 au around a G-type star, and with a mass range that allows retention of moderate atmospheres, and perhaps even plate tectonics, super-Earths have become the focus of extensive observational campaigns to search for habitable planets, and have stimulated considerable research on their origin, composition and interior dynamics (Morbidelli & Raymond, 2016).

By combining radial velocity and transit data, bulk density measurements have been made for more than 100 super-Earths (Marcy et al., 2014). Most planets larger than  $1.5 - 2R_{\oplus}$  have low measured bulk densities and may thus be ‘mini-Neptunes’ rather than ‘super-Earths’ (Weiss & Marcy, 2014; Lopez & Fortney, 2014; Rogers, 2015; Wolfgang & Lopez, 2015; Venturini & Helled, 2017). Most planets smaller than  $\sim 1.5R_{\oplus}$  have bulk densities expected of rocky planets, but exceptions such as Kepler-79 exist (Jontof-Hutter et al.,



2014). However, the detailed compositions of even the best-measured super-Earths remain poorly-constrained (e.g. Adams et al., 2008). Late-stage giant impacts may have a further significant influence on atmospheric content and composition (e.g. Liu et al., 2015f), while atmospheric loss through X-ray or extreme ultraviolet irradiation is likely to be minimal (Lammer et al., 2014b).

Super-Earths are often found in multi-planet systems, usually in compact orbital configurations with low eccentricities and low mutual inclinations (Lissauer et al., 2011b; Fang & Margot, 2012a; Tremaine & Dong, 2012; Fabrycky et al., 2014). Their orbital separations, measured in orbital period ratio or in mutual Hill radii, are similar to those among the solar system's terrestrial planets (Fang & Margot, 2013).

**Formation** While invoking the existence of a large population of embryos close to their host stars can reproduce some properties of the observed super-Earth systems (Hansen & Murray, 2013), the hypothesis of direct *in situ* accretion poses certain problems. If super-Earths formed locally, the implied ‘minimum-mass solar nebula’ (§10.3.1) is both extremely dense, some 10–100 times more massive than the nebula inferred from the solar system or other young stars, and with a broad range of surface density profiles among different systems, difficult to reconcile with the structure of an actual protoplanetary disk (Raymond et al., 2008c; Chiang & Laughlin, 2013; Lee et al., 2014c; Raymond & Cosou, 2014; Schlichting, 2014). Moreover, Mulders et al. (2015c) found that the population of super-Earths orbiting M stars is statistically different than that orbiting FGK stars, with M stars hosting more small super-Earths and fewer large ones compared with FGK stars.

Their higher masses and host star proximity also imply short orbital migration time scales, much shorter than the typical disk lifetime (Rogers et al., 2011; Ogihara et al., 2015b; Inamdar & Schlichting, 2015).

The requirements for high surface densities may be alleviated if solid material is transported inwards from the outer disk, either in the form of protoplanetary cores (Ward, 1997a) or planetesimals (Hansen & Murray, 2012). The transport of small pebbles, collecting at appropriate locations and forming planets through a sequential ‘inside-out’ process, has also been suggested, and described in Section 10.4.4.

**Other considerations** To explain the fact that their core masses are large enough to trigger runaway gas accretion, yet they have accreted atmospheres with only a few percent of their total mass, various hypotheses have been proposed. It has been suggested that they formed late on, in transition-like disks, as their gas disks were about to clear (Lee et al., 2014c; Lee & Chiang, 2016), or in short-lived disks ( $\lesssim 2$  Myr) in which photoevaporation completes while the planets are still in a slow phase of gas accretion (Alessi et al., 2017).

Tidal heating of a young (and therefore inflated) planet can inhibit gas cooling and provides another barrier to further ac-

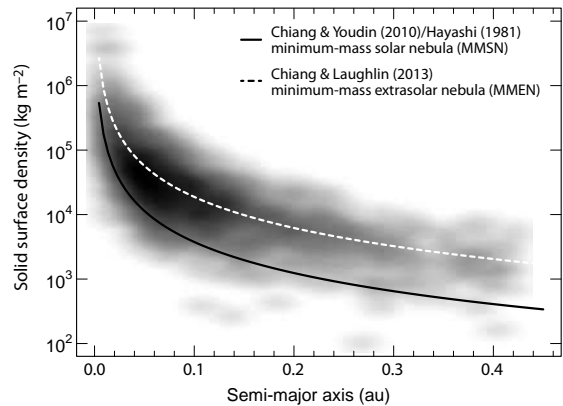


Figure 10.26: Solid surface density profile  $\Sigma_{\text{solid}}$  of the Chiang & Laughlin (2013) minimum-mass extrasolar nebula (MMEN). Background shading indicates the density of points in the semi-major axis–solid surface density diagram for Kepler KOIs, defined as  $\Sigma_{\text{solid}} = M_p / (2\pi a_p^2)$ . The solid curve shows the standard minimum-mass solar nebula (MMSN Hayashi, 1981) as parameterised by Chiang & Youdin (2010). The dashed curve shows the fiducial MMEN of Chiang & Laughlin (2013). There is insufficient solid material in the MMSN nebula to form the observed KOIs *in situ*, in which case the migration of solids is required to explain the KOIs. From Schlaufman (2014, Figure 1), by permission of IOP Publishing/AAS.

cretion. Ginzburg & Sari (2017b) showed that the growth of super-Earth atmospheres halts for planets with  $P \sim 10$  d if their initial eccentricities are of order  $e \sim 0.2$ , providing a robust mechanism that can simultaneously explain why these planets did not become gas giants, while also accounting for the deficit of low-density planets closer to the star, where the tides are even stronger. Thermal feedback induced by turbulent diffusion was suggested by Yu (2017). Envelope growth may be slowed if it is not in hydrostatic balance as a result of complex accreting gas flows (Lambrechts & Lega, 2017).

Other models suggest that the inward transport occurred at larger size scales via (large) planetesimal disk migration, possibly with subsequent embryo merging (Terquem & Papaloizou, 2007; Ogihara & Ida, 2009; Ida & Lin, 2010; McNeil & Nelson, 2010; Matsumoto et al., 2012; Hasegawa & Pudritz, 2013; Cosou et al., 2014; Izidoro et al., 2014b; Kenyon & Bromley, 2014a; Liu et al., 2015b; Matsumoto et al., 2015b; Ogihara et al., 2015b; Bitsch & Johansen, 2016; Coleman & Nelson, 2016b).

The formation of icy super-Earths at 125–250 au, via a second runaway growth phase, could result in the gaps and structures seen in some debris disks (Kenyon & Bromley, 2015b).

**Absence in the solar system** Morbidelli & Raymond (2016) have suggested that the absence of super-Earths in the inner solar system (Planet Nine may be a super-Earth in the outer regions, §12.5.8), or that there are no terrestrial planets interior to Mercury, may be related to the initial distribution of embryos (Hansen, 2009); to the blocking of the inward migration of more distant embryos by Jupiter (Izidoro et al., 2015b); to the turbulent structure of the protoplanetary disk (Martin & Livio, 2016); or linked to more hybrid models of accretion and migration (Raymond et al., 2016). Or it may be that the primordial solar system contained systems of super-Earths that were later destroyed (Volk & Gladman, 2015; Batygin & Laughlin, 2015; Martin & Livio, 2016).

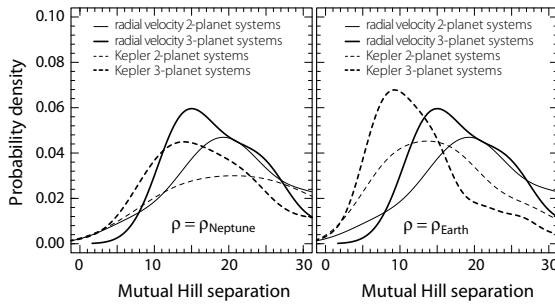


Figure 10.27: Distributions of mutual Hill separation of the Kepler and radial velocity multi-planet systems. Left: derived assuming that the typical densities of the Kepler multi-planet systems is  $\rho = \rho_{\text{Neptune}} = 1.6 \text{ Mg m}^{-3}$ . Right: derived assuming  $\rho = \rho_{\oplus} = 5.5 \text{ Mg m}^{-3}$ . If  $\rho = \rho_{\text{Neptune}}$ , then both distributions are statistically indistinguishable. From Schlaufman (2014, Figure 3), by permission of IOP Publishing/AAS.

**Multiple close-in super-Earths** The multiple close-in super-Earths/sub-Neptunes systems discovered by Kepler, and often occurring in resonant chains, such as the 6-planet Kepler-11 and the 4-planet Kepler-223, pose a further challenge for formation models. In addition, there are an excess of planet pairs just exterior to the 2:1 and 3:2 mean motion resonances, compared to the pairs just interior to these resonances (§6.30.4), which is not easily explained by *in situ* formation.

Again, several studies have proposed that these systems can be formed *in situ*, invoking various specific conditions to address the issues of orbital migration, and to the requirements of a very high surface density of solid material in the inner disk (e.g., Hansen & Murray, 2012, 2013; Ikoma & Hori, 2012; Chiang & Laughlin, 2013; Dawson et al., 2016; Tan et al., 2016). Figure 10.26 illustrates the required surface density of solid materials required for the ‘minimum-mass extrasolar nebula’ (MMEN) in such models, compared to that of the standard minimum-mass solar nebula (MMSN; §10.3.1).

Other studies support the alternative *ex situ* assumption, that is, that they formed farther out in the disk and, during or after formation, migrated inward to their present positions through interactions with the protoplanetary disks (e.g. McNeil & Nelson, 2010; Rogers et al., 2011; Lopez et al., 2012; Mordasini et al., 2012b; Migaszewski et al., 2012; Bodenheimer & Lissauer, 2014; Hands et al., 2014; Chatterjee & Ford, 2015; Fung & Chiang, 2017). The latter model has been considered because of the difficulties in forming planets *in situ* in the very inner regions of disks (Bodenheimer et al., 2000), well inside the orbit of Mercury in the solar system.

Schlaufman (2014) used the *in situ* minimum-mass extrasolar nebula of Chiang & Laughlin (2013) to predict the implied occurrence of (undetected) outer gas giants, based on the giant planet–metallicity relation from radial velocity observations (Equation 10.24), find-

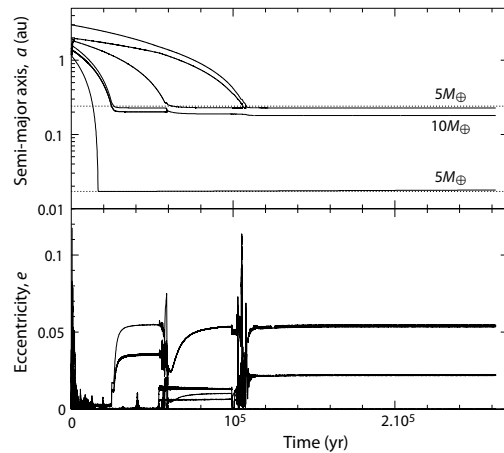


Figure 10.28: Simulations of the formation of Kepler-10, showing evolution of  $a$  (in units of  $\log \text{ au}$ , upper plot) and  $e$  (lower plot) of the 14 cores in the system versus time. Initially, the 6 outer cores are  $2M_{\oplus}$ , while the others are  $1M_{\oplus}$ . Solid lines represent different cores, with lines terminating prior to collision. In the upper plot, dotted lines indicate the inner cavity (0.017 au initially, 0.24 au after  $1.6 \times 10^4 \text{ yr}$ ). The disk is removed after  $1.6 \times 10^5 \text{ yr}$ . Three cores remain at the end of the simulation, with masses shown in the upper plot. From Terquem (2014, Figure 1), © Oxford University Press.

ing a discrepancy between the predicted numbers of giant planets based on such an *in situ* model, and the numbers observed, and so arguing that some degree of migration must still be important. In the process, constraints on the typical density of the close-packed Kepler system comes from a requirement in consistency between the inferred mutual Hill separations from the Kepler and radial velocity samples (Figure 10.27).

Uncertainties in the theory of planet–disk interactions (Kley & Nelson, 2012; Chiang & Laughlin, 2013) mean that it remains unclear whether planet formation with migration can explain the mass distribution as well as the orbital period distribution of Kepler’s super-Earth/sub-Neptune planets (Howard et al., 2010b).

An argument against the *ex situ* picture is that convergent migration in a multiple system might be expected to lead to capture into mean motion resonances, while most of the Kepler systems do not appear to be in resonance (Lissauer et al., 2011a). Goldreich & Schlichting (2014) proposed an instability mechanism that would allow the planets to move *through* resonances, although Deck & Batygin (2015) concluded that the time spent in resonance significantly exceeds the time during which they are out of resonance.

Other mechanisms invoked to move planets out of resonance include dissipative effects (Delisle et al., 2012; Lithwick & Wu, 2012; Batygin & Morbidelli, 2013b), stochastic effects during migration (Rein, 2012), tidal effects caused by planet–wake interactions (Baruteau & Papaloizou, 2013), the effects of small orbit eccentric-

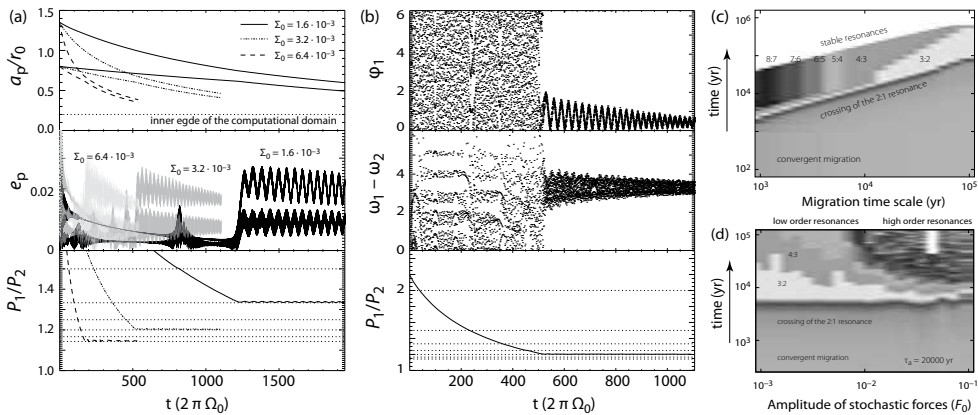


Figure 10.29: Simulations of the formation of the 2-planet 7:6 mean motion resonance system Kepler-36. (a) hydrodynamic simulation without stochastic forces, for three different values of the surface density  $\Sigma_0$  (8, 16, and 32 times the minimum-mass solar nebula). For  $r_0 = 1$  au,  $t$  is in years. Top panel: semi-major axis  $a$ ; middle panel: eccentricity  $e$ , where the largest value belongs to the inner, lower mass planet; bottom panel: period ratio; horizontal dotted lines show first order commensurabilities, from 3:2 (top) to 8:7 (bottom); (b) evolution of the resonant angle  $\phi_1$  for the 6:5 resonance (top panel), difference between longitudes of pericentre  $\varpi$  (middle panel) and period ratio (bottom panel) for a system without stochastic forces for  $\Sigma_0 = 3.2 \times 10^{-3} M_\star / r_0^2$ ; (c) N-body simulation results with smooth migration. Stable resonances form for migration rates longer than a few kyr, with the resonance formed determined by the migration rate (grey scale encodes period ratios); (d) N-body simulations results with both smooth and stochastic migration. Stochastic forces assume a disk with  $\Sigma_0 = 3.2 \times 10^{-3}$ . Stable resonances form for migration rates longer than a few kyr. For  $F/F_0 > 0.01$ , resonances can break up, and planets can be captured into high- $p$  resonances. From Paardekoooper et al. (2013, Figures 1, 2, and 6), © Oxford University Press.

ities (Batygin, 2015), instabilities following gas dissipation (Izidoro et al., 2017), outer giant planet scattering (Huang et al., 2017b), and a one-sided ‘magnetospheric rebound’ at the interface of the disk and an empty magnetospheric cavity, as applied to models of Kepler-170 and Kepler-180 (Liu et al., 2017a; Liu & Ormel, 2017).

**Individual systems** Various systems have been modeled in detail, attempting to replicate close-packed systems of particularly high multiplicity, or which display complex resonance and near-resonance states. The following gives a synopsis of three specific systems.

- *Kepler-10*: this 2-planet system includes Kepler-10 c which, with a transit-derived radius of  $2.35R_\oplus$ , was expected to have a gaseous envelope. However, together with its mass of  $17M_\oplus$  determined by radial velocity measurements, it is instead inferred to have a high density of  $\sim 7 \text{ Mg m}^{-3}$ , and therefore likely to be solid (Dumusque et al., 2014b). This was unexpected, as it was believed that the critical core mass, above which accretion of a massive gaseous envelope occurs, is  $\sim 10M_\oplus$ .

Terquem (2014) investigated the conditions required for the 3 and  $17M_\oplus$  planets to have formed through collisions and mergers within an initial population of embryos. From a large number of N-body simulations, they showed that the total mass of the initial population had to be significantly larger than the present masses of the two planets, and that the two planets must have formed much further away than their present location (either through planetesimal accretion, or through collisions among a population of cores), at a distance of at least a few au (Figure 10.28). The planets had to grow fast enough to detach themselves from the population of remaining, less massive, cores, and so migrate in to their present location.

Terquem (2014) also computed the critical core mass beyond which a massive gaseous envelope would have been accreted, and showed that it is larger than  $17M_\oplus$  if the planetesimal accretion rate onto the core is larger than  $10^{-6} M_\oplus \text{ yr}^{-1}$ . For an accretion rate between  $10^{-6}$  and  $10^{-5} M_\oplus \text{ yr}^{-1}$ , the  $17M_\oplus$  core would not be expected to have accreted more than about  $1M_\oplus$  of gas. The system probably formed in a rather massive disk, which favours the formation of massive planets which migrate rapidly, and end up on short orbits (Thommes et al., 2008b). The results also suggest that systems like Kepler-10 may not be unusual.

- *Kepler-11*: this 6-planet system provides an interesting test case for super-Earth formation models: all six orbit within 0.46 au, the inner 5 with masses  $2 - 8M_\oplus$  (Lissauer et al., 2011a; Ikoma & Hori, 2012; Lissauer et al., 2013). Models, assuming either *in situ* formation or *ex situ* assembly combined with migration (Bodenheimer & Lissauer, 2014; Howe & Burrows, 2015; D’Angelo & Bodenheimer, 2016), involve details of both the gaseous envelope and the condensed core structures, the accretion of gas and solids, the disk’s viscous and thermal evolution, photoevaporation and disk–planet interactions, and the planet’s evaporative mass loss after disk dispersal. Both successfully reproduce measured radii, masses, and orbital distances of the planets, except for the radius of Kepler-11 b, which loses its entire gaseous envelope shortly after formation.

*In situ* models predict a very massive inner disk, whose solid surface density varies from over  $10^5$  to  $10^4 \text{ kg m}^{-2}$  at distances 0.1–0.5 au, and in which planetary interiors can only be composed of metals and highly refractory materials. *Ex situ* models predict a relatively low-mass disk, whose initial density varies from  $\sim 100$  to  $\sim 50 \text{ kg m}^{-2}$  at 0.5–7 au. D’Angelo & Bodenheimer (2016) nevertheless concluded that both possibilities remain viable options.

• *Kepler-36*: this is an unusually closely-spaced system, lying near to the 7:6 mean motion resonance, and comprising two planets ( $M_{\text{inner}} \sim 4M_{\oplus}$ ,  $M_{\text{outer}} \sim 8M_{\oplus}$ ) of dissimilar densities spaced extremely close together,  $\Delta a \sim 0.01$  au (such that, at closest approach, the outer planet would appear twice as large as the full moon as viewed from the inner planet). While it is held that mean motion resonances can form robustly by convergent migration, and while *Kepler-36* is not special in terms of period ratio (not being exactly in the 7:6 mean motion resonance), it is unusual in terms of stability, being situated very close to unstable regions in parameter space (Deck et al., 2012): for most of the orbital solutions the Lyapunov time scale (§10.9) is of the order of a few hundred years, compared to many Myr in the solar system (Hayes, 2007), meaning that the system is chaotic, in the sense that the memory of initial conditions is lost on short time scales, even though the system is stable over much longer time scales.

Current models explain how the *Kepler-36* planets arrived in such a precarious island of stability in the following way (Paardekooper et al., 2013; Quillen et al., 2013; Liu et al., 2015f). The different mean planet densities suggests that they formed in different locations, with only the outer planet capturing a significant amount of gas from the residual disk. Their close proximity to the central star furthermore suggests that both have migrated inward a significant distance. Combining both leads to the formation scenario of convergent migration, a mechanism that is known to lead to resonant pairs of planets, stimulated by the discovery of GJ 876 (§2.12.4, §10.8.2). A giant impact may have contributed to the devolatilisation (Liu et al., 2015f).

Convergent migration into the 7:6 mean motion resonance could lead to a stable planetary system and, as suggested by Deck et al. (2012), subsequent tidal evolution, either by interaction with the star (Papaloizou, 2011; Lithwick & Wu, 2012; Batygin & Morbidelli, 2013b), or with the remnant disk (Baruteau & Papaloizou, 2013), could drive the planets slightly out of the 7:6 resonance. The final orbits in these scenarios tend to be Lagrange stable, even though large parts of the parameter space are chaotic and unstable (Figure 10.29).

Mechanisms for passing through various other resonances, on their way to the present 7:6 resonance, invoke high disk masses, in which the low-mass planets can be shepherded into compact configurations (Papaloizou & Szuszkiewicz, 2005), but at the same time requiring formation early on in the life of the disk, along with survival throughout the fast migration (with a migration time scale of less than a thousand years) associated with massive disks.

#### 10.7.4 Planetary satellites (exomoons)

Much of what is known about the formation and expected properties of exomoons is derived from knowledge of the solar system (Section 12.5.10). Specific detection prospects are considered in Section 6.22, and habitability in Chapter 11 (box, page 627).

By analogy with inferred processes in the early solar system, exomoons are likely to have formed through one of three principal processes: as a by-product of planetary formation in a circumstellar disk, as a result of massive impacts, or through various capture processes.

**Specific studies** Specific studies of the formation and evolution of exomoons include studies of their Hill stability and resulting orbit constraints (Donnison, 2010b, 2014), the expected

formation rates through collisional impacts (Elser et al., 2011), and through capture by giant planets, including 3-body binary planetesimal exchange in the case of irregular satellites (Suetugu et al., 2011; Quillen et al., 2012; Suetsugu & Ohtsuki, 2013; Williams, 2013), post-capture dynamical evolution (Porter & Grundy, 2011), and tidal decay lifetimes (Sasaki et al., 2012).

An exomoon accompanying an inwardly-migrating giant planet is expected to result in ejection or collision before its orbit is affected by tidal evolution, such that if exomoons are detected around close-in planets, they are likely to have been captured rather than have formed *in situ* (Namouni, 2010). Exomoon survival prospects as a result of planet–planet scattering (§10.10.4) appear to be limited, with the consequence that single planets on eccentric orbits are unlikely to be favourable exomoon hosts (Gong et al., 2013).

## 10.8 Resonances

Orbital resonances arise when two orbiting bodies exert a regular, periodic gravitational influence on each other as a result of simple numerical relationship between frequencies or periods. The repetitive force between them does not average to zero over long time scales, and secular theory is therefore not applicable. The periods involved can be the rotation and orbit periods of a single body (spin–orbit coupling), the orbital periods of two or more bodies (orbit–orbit coupling), or other more complicated combinations of orbit parameters, such as eccentricity versus semi-major axis or orbit inclination, as in Lidov–Kozai resonance (§10.10.6).<sup>4</sup>

Resonances can result in unstable interactions, in which the bodies exchange momentum and their mutual orbits evolve. In other circumstances a resonant system can be stable and self-correcting, so that the bodies remain in resonance indefinitely. Some of the many manifestations of orbital resonances observed in the solar system (§12.4) have already been observed in the orbits of exoplanets (e.g. Kley, 2010).

### 10.8.1 Mean motion resonance

A significant number of multi-planet systems have orbital periods which appear to be related by commensurabilities of the form  $P_1/P_2 \simeq i/j$ , where subscripts 1, 2 refer to the inner and outer planets, and  $i$  and  $j$  are small integers. These commensurabilities arise from dynamical considerations; as noted below, exact commensurability is not a resonance condition *per se*.

<sup>4</sup> The term ‘secular’, and the associated use of ‘secular time scale’, describes trends or long-term variations (e.g., in planetary orbits) that contrast with periodic phenomena. Whether a trend is perceived as secular may depend on the available time scale: a secular variation over a time scale of centuries may be part of a periodic variation over much longer periods. Lithwick & Wu (2011), for example, define ‘secular’ as orbit-averaged interactions which dominate over long time scales.

The concepts and analytical tools used to understand resonance phenomena in the solar system have been developed over more than a century (Peale, 1976). Murray & Dermott (2000) provide an exposition of secular and resonant theory, including a detailed treatment of mean motion resonances. The following summarises the concepts and terminologies most widely encountered in exoplanet studies.

Consider two planets moving in circular co-planar orbits which satisfy

$$\frac{n_2}{n_1} \approx \frac{p}{p+q}, \quad (10.26)$$

where  $n_1 = 2\pi/P_1$  and  $n_2 = 2\pi/P_2$  are the mean motions of the inner and outer planets, and  $p$  and  $q$  are integers. If the two planets are at *conjunction* at time  $t = 0$  (in alignment, independently of where along the orbits this is), then the next conjunction occurs when

$$n_1 t - n_2 t = 2\pi, \quad (10.27)$$

and the time interval between successive conjunctions is therefore given by

$$\Delta T = \frac{2\pi}{n_1 - n_2} = \frac{p}{q} \frac{2\pi}{n_2} = \frac{p}{q} P_2 = \frac{p+q}{q} P_1, \quad (10.28)$$

from which

$$q \Delta T = p P_2 = (p+q) P_1. \quad (10.29)$$

For  $q = 1$ , each planet completes an integer number of orbits between successive conjunctions, with every conjunction occurring at the same longitude in inertial space. More generally, every  $q$ -th conjunction occurs at the same longitude, with  $q$  defining the *resonance order* of the *mean motion resonance*.

If the outer planet moves in an eccentric orbit with  $e_2 \neq 0$  and  $\dot{\omega}_2 \neq 0$ , i.e. if the longitude of pericentre precesses, then resonances can still occur if

$$\frac{n_2 - \dot{\omega}_2}{n_1 - \dot{\omega}_1} = \frac{p}{p+q}, \quad (10.30)$$

in which case

$$(p+q)n_2 - p n_1 - q \dot{\omega}_2 = 0. \quad (10.31)$$

Now, every  $q$ -th conjunction takes place at the same point in the outer planet's orbit, but no longer at the same longitude in inertial space. This relation encapsulates the dynamical significance of mean motion resonance. It also shows that the near (but not necessarily exact) commensurabilities in orbital periods are a consequence of (typically) small orbit precession.

Expressed in terms of the mean longitude,  $\lambda$ , and generalised to both orbits, corresponding *resonant arguments* (or resonant angles),  $\phi$ , can be identified as

$$\phi = (p+q)\lambda_2 - p\lambda_1 - q\dot{\omega}_{1,2}. \quad (10.32)$$

**Physics of resonance:** Peale (1976) gives a heuristic physical description of resonance, reproduced here in outline.

Consider a test particle of negligible mass moving in an eccentric outer orbit around a more massive object. Assume a fixed line of apsides, precise commensurability of the mean motions, and conjunctions occurring close to, but not at, apocentre.

Net tangential forces increase the orbital angular velocity of the test particle, moving the successive conjunctions closer to apocentre. Similarly, conjunctions occurring after apocentre move successive conjunctions back towards apocentre. Conjunctions thus librate stably about the apocentre, preserving commensurability. A secular variation in the pericentre longitude  $\dot{\omega}$  does not alter this fundamental libration. Similarly, pericentre conjunctions correspond to unstable equilibrium (Figure 10.30).

For conjunctions occurring precisely at the apocentre of the outer test particle, radial forces accelerate it towards the primary, resulting in a trajectory slightly inside its nominal orbit. The test particle accordingly reaches its closest approach to the primary slightly earlier, and the line of apsides has rotated in a retrograde sense as a result. This regressional motion of the line of apsides can reduce, or even dominate, the normal prograde motion resulting from the oblateness of the primary. This type of orbital resonance also leads to a secular increase of the eccentricity.

For the 2:1 and 3:1 resonances, for example, the resonant arguments take the form

$$\phi(2:1) = 2\lambda_2 - \lambda_1 - \dot{\omega}_{1,2} \quad (p=1, q=1), \quad (10.33)$$

$$\phi(3:1) = 3\lambda_2 - \lambda_1 - 2\dot{\omega}_{1,2} \quad (p=1, q=2). \quad (10.34)$$

The resonant argument measures the angular displacement of the two planets at their point of conjunction, with reference to one or other pericentre.

Resonant dynamics are important if  $\phi$  varies slowly relative to the orbital motion. If, rather than circulating, the resonant argument is stationary, or if it *librates* (i.e. oscillates), then the planets are in resonance. *Exact resonance* describes the particular combination of mean motions and precession rates for which the time variation of a particular resonant argument is zero ( $\dot{\phi} = 0$ ). The term *deep resonance* is used to describe systems with small libration amplitudes. Outside of exact resonance, the orbital elements  $a, e, \dot{\omega}$  and the resonant argument  $\phi$  all evolve with time.

The *super-period* characterises the time it takes for the line of conjunctions to circulate by one full revolution (e.g. Agol et al., 2005; Lithwick et al., 2012)

$$P_{\text{super}} = \frac{1}{|(j+1)/P_2 - j/P_1|}. \quad (10.35)$$

It also provides a measure of distance from the  $j+1:j$  mean motion resonance. Many Kepler multi-planet systems show anti-correlated sinusoidal transit timing variations at this period (§6.20).

**The more general case** In the more general analysis of orbital resonances, the time derivatives of the orbital el-

ements are expressed in terms of partial derivatives of the disturbing function. The general form of the argument which then appears in the expansion of this disturbing function is (Peale 1976, eqn 7; Murray & Dermott 2000, eqn 8.18)

$$\phi = j_1 \lambda_1 + j_2 \lambda_2 + k_1 \tilde{\omega}_1 + k_2 \tilde{\omega}_2 + i_1 \Omega_1 + i_2 \Omega_2, \quad (10.36)$$

where the variables  $\lambda$ ,  $\omega$ ,  $\Omega$  are confined to the arguments (angular dependencies) of the two orbits. Equation 10.32 is a special case of this more general form. More complex resonances have different numbers of resonant arguments involving various permutations of these terms, classified according to the relevance of the coefficients  $i, j, k$  (e.g. Peale, 1976, Table 2). The majority of resonance configurations are characterised by only one librating argument (Michtchenko et al., 2008a,b).

Motion near the 2:1 (and other first-order) resonances depends on initial conditions, and includes libration (in  $a$ ,  $e$ , and  $\phi$ ), apocentric libration, and inner and outer circulation (e.g. Murray & Dermott, 2000, Figure 8.16). The phase space boundary, or *separatrix*, which separates librating (or oscillating) from circulating regimes is determined by the total energy.

A definition of ‘resonant’ which overcomes shortcomings when defined in terms of resonant arguments (e.g. Petrovich et al., 2013; Armstrong et al., 2015b) is a trajectory that evolves in the region of phase space surrounded by the separatrices of a given integrable system Hamiltonian (Morbidelli, 2002).

**Apsidal motion** Within the class of 2:1 resonances, for example, configurations of stability or instability are determined by the eccentricities of the inner and outer planets, while their apsidal alignment may also display different behaviour in different systems (Figure 10.30).

As first observed for the two planets GJ 876 b and c, both of the lowest-order eccentricity-type mean motion resonance variables (Equation 10.33)

$$\begin{aligned} \phi_1 &= 2\lambda_2 - \lambda_1 - \tilde{\omega}_1 \quad \text{and} \\ \phi_2 &= 2\lambda_2 - \lambda_1 - \tilde{\omega}_2 \end{aligned} \quad (10.37)$$

librate around  $0^\circ$ . So therefore does the (apsidal resonance variable) quantity

$$\phi' = \tilde{\omega}_1 - \tilde{\omega}_2 \equiv \phi_1 - \phi_2, \quad (10.38)$$

meaning that the pericentres remain nearly aligned while librating, with conjunctions occurring (in this case) when both planets are near to their pericentres. The deep resonance in GJ 876 is not only an inference from dynamical modeling, but the associated retrograde pericentre precession has been observed for many orbital periods as a consequence of their relatively close-in orbits ( $P_b \sim 61$  d,  $P_c \sim 30$  d).

A number of the 2:1 resonant exoplanet systems are observed to be in such a state of apsidal alignment,

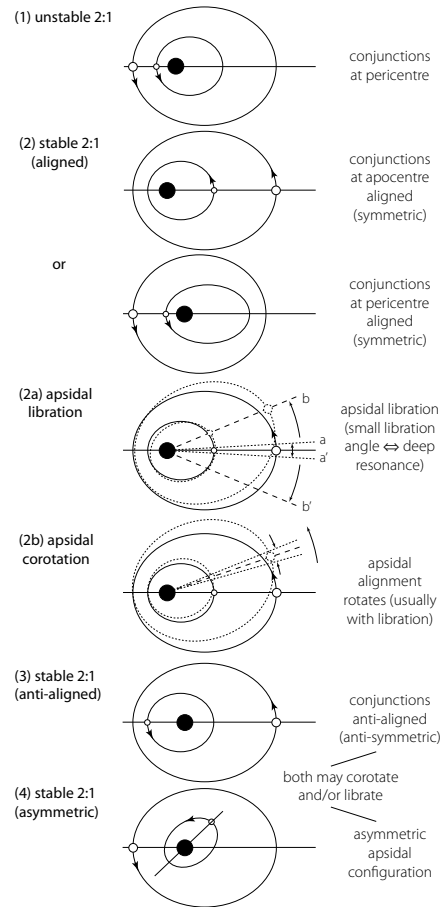


Figure 10.30: The 2:1 mean motion resonance, and associated apsidal motion: (1) conjunctions at close approach (here at pericentre) are unstable; (2) for stable resonances, apsidal alignment may librate over many orbits (2a), and orbital periods will not be precisely commensurate. Small libration angles (of a few degrees) correspond to deep resonance. Libration angles may be tens of degrees, or the alignment angle may continuously rotate (2b), with additional libration superimposed; (3) conjunctions may also be anti-aligned and, again, either circulating and/or librating or, in theory, asymmetric (4).

with their apocentres either aligned (e.g. GJ 876 and HD 37124) or anti-aligned (e.g. HD 60532, HD 73526, HD 155358, HIP 14810). The limited statistics suggest that alignment and anti-alignment might occur with approximately equal frequency (Zhou & Sun, 2003; Barnes & Greenberg, 2006a, 2007a; Barnes, 2008).

When it does occur, small-amplitude *apsidal libration* may manifest itself around equilibrium angles of  $0^\circ$  (aligned, or symmetric) or  $180^\circ$  (anti-aligned, or antisymmetric), but any other (asymmetric) angle can in principle serve as a stable equilibrium (Beaugé et al., 2003; Ji et al., 2003c,d; Lee, 2004; Voyatzis & Hadjidemetriou, 2005; Beaugé et al., 2006; Libert & Henrard, 2006; Marzari et al., 2006).

Not all theoretically-possible 2:1 resonance configurations can be achieved through migration alone, and their existence would provide further constraints on the system's evolution (Lee, 2004).

One mechanism proposed for establishing a significant apsidal libration in a pair of planets initially on nearly circular orbits invokes an impulsive generation of eccentricity, perhaps caused by the ejection of a planet (Malhotra, 2002). The model can match the aligned orbits observed in  $\nu$  And (Chiang et al., 2001). An alternative mechanism, invoking adiabatic perturbations, could follow from tidal torques in a massive primordial disk providing the eccentricity excitation for the outer planet (Chiang & Murray, 2002). Malhotra (2002) suggested that a large apsidal libration amplitude would favour the impulsive mechanism, whereas small amplitudes (as for GJ 876) would favour the adiabatic.

In systems initially in a 3:1 mean motion resonance, dynamical studies show that apsidal librations are also common. Maps of dynamical stability nevertheless show a complicated structure in phase space, with chaos and order coexisting and alternating as the initial eccentricities or apsidal phases evolve (Voyatzis, 2008).

**Recognising resonance** Current observations of transiting or radial velocity systems typically do not allow definitive assignment to a mean motion resonance: definition is via the librating or oscillating behaviour of some linear combination of resonant arguments, while the temporal evolution of mean longitudes, or longitudes of pericentre, are in general not available.

As a result, a common practice is to use orbital period ratios as a proxy for resonance. The frequent occurrence of Kepler systems with ratios of  $\sim 2:1$ ,  $\sim 3:1$ ,  $\sim 3:2$  (Lissauer et al., 2011b; Quarles et al., 2012c), for example, suggests that these commensurabilities are a significant tracer of formation, regardless of whether specific planets are actually locked in a mean motion resonance.

Astrometric detection of multiple planets in mean motion resonance, in the context of the Chinese STEP mission, has been detailed by Wu et al. (2016a).

### 10.8.2 Resonance trapping and migration

The stability of a system once in resonance is understood. The reason for the existence of so many multiple exoplanets in mean motion resonance was, initially, somewhat less evident.

In the solar system, orbital commensurabilities have long been attributed to dissipative processes early in its formation, or to slow differential increase in the semi-major axes of satellite orbits as a result of tidal transfer of angular momentum from the primary (Goldreich, 1965; Peale, 1976). Specifically, Goldreich (1965) showed that for a pair of satellites under the influence of their planet's tidal forces, initially with non-commensurable

mean motions, the inner will spiral outwards until their periods become commensurable, thereafter maintaining this state as the orbits evolve.

**Convergent migration** The present consensus is that the observed orbital resonances could not have simply formed *in situ*. Rather, the evidence from both hydrodynamic and N-body simulations is that some planets have become trapped in specific resonances as a result of differential *convergent migration*, in which dissipative processes steadily altered their semi-major axes and eccentricities. In turn, the occurrence of orbital resonances constitutes strong evidence for such migration and associated *resonance trapping*, or 'resonance capture', albeit potentially driven by a variety of mechanisms, having occurred.

As shown by Kley et al. (2004), slow migration of two giant planets embedded in a protoplanetary disk can end with either a 2:1 or 3:1 resonant system, depending on the rate of migration. For masses in the range  $1 - 4M_{\oplus}$ , Papaloizou & Szuszkiewicz (2005) found somewhat similar behaviour using both hydrodynamic and N-body simulations. Slow convergent migration results in period ratios given by first-order commensurabilities  $p + 1:p$  with  $p$  as small as 1–2.

Various studies of the migration of individual planets have characterised the motion by a migration rate,  $\dot{a}/a$ , and an eccentricity damping rate,  $\dot{e}/e$ . Corresponding e-folding times are given by

$$\tau_a = -\left(\frac{\dot{a}}{a}\right)^{-1} \quad \text{and} \quad \tau_e = -\left(\frac{\dot{e}}{e}\right)^{-1}. \quad (10.39)$$

GJ 876 is one of the most studied system in a mean motion resonance (§2.12.4). Lee & Peale (2002) found that for a sufficiently slow migration, the final state depends only on the ratio of the e-folding times  $K = \tau_a/\tau_e$ . Resonant capture is suppressed for high migration rates, but depends on the detailed form of the resonant argument (Quillen, 2006b; Quillen & Faber, 2006).

From hydrodynamical calculations it has been proposed that  $K$  assumes values close to unity, reflecting the mass and viscosity of the protoplanetary disk (Kley et al., 2004). If such a system is subject to adiabatic migration, a given value of  $K$  results in specific values of the final eccentricities (Lee & Peale, 2002).

Detailed behaviour varies with initial conditions, orbital configuration (prograde, polar, and retrograde), multiplicity, mass and mass ratios, disk structure, radial drift rate, and associated damping conditions (e.g. Bryden et al., 2000; Kley, 2000; Snellgrove et al., 2001; Lee & Peale, 2002; Nelson & Papaloizou, 2002; Papaloizou, 2003; Thommes & Lissauer, 2003; Lee, 2004; Kley et al., 2004, 2005; Matsumura et al., 2010b; Ketchum et al., 2011b; Libert & Tsiganis, 2011b; Mustill & Wyatt, 2011; Matsumoto et al., 2012; Ogiyama & Kobayashi, 2013; Pierens et al., 2013; Bodman & Quillen, 2014; Goldreich

& Schlichting, 2014; Podlowska-Gaca & Szuszkiewicz, 2014; Zhang et al., 2014c; Liu et al., 2015b; Migaszewski, 2015; Namouni & Morais, 2015; Reyes-Ruiz et al., 2015; Liu et al., 2016a; Hardy & Gong, 2017; Namouni & Morais, 2017; Ramos et al., 2017; Xu & Lai, 2017).

These complex dynamical phenomena are capable of populating a wide range of final orbital configurations which cannot easily be visualised in their entirety. As just one example, an enhanced ‘dynamical corridor’ for capture into high-order inner prograde resonances exists for initial inclinations in the range  $50 - 80^\circ$ , especially at the inner 5:2 resonance which capture probability peaks at 80–90% (Namouni & Morais, 2017).

More on the phenomenon of resonance trapping is given under the topic of migration (§10.10.2), and further observational evidence under the description of individual systems (§2.12.4). Resonant trapping due to type II migration is now considered as the main formation mechanism for resonant multi-planet systems.

**Resonance pile-up and asymmetry** Analysis of Kepler transiting systems reveals a distinct asymmetry or ‘pile-up’ of planet pairs just wide of certain (low-order) period commensurabilities (e.g. Fabrycky et al., 2014). This has led to the concepts of ‘dissipative divergence’ and ‘resonance breaking’, for example through stochastic orbital forcing induced by turbulent density fluctuations within the nebula (Batygin & Morbidelli, 2013b; Lee et al., 2013c; Petrovich et al., 2013; Delisle et al., 2014; Delisle & Laskar, 2014; Xie, 2014a; Chatterjee & Ford, 2015; Batygin & Adams, 2017). This is discussed further in Section 6.30.4.

### 10.8.3 Specific resonances

**Laplace resonance** In a three-body resonance, period ratios between successive pairs satisfy  $n_1/n_2 \sim p/q$  and  $n_2/n_3 \sim r/s$ , with integer  $p, q, r, s$ . The case where the period ratio between consecutive pairs is  $n_1/n_2 \sim n_2/n_3 \sim 2/1$ , is a particular case of a three-body resonance called the *Laplace resonance*. In the solar system, the Galilean satellites Io, Europa and Ganymede constitute the only known example (see Figure 2.42).

Amongst radial velocity systems, GJ 876 is in a Laplace resonance (§2.12.4), while HD 40307 (Papaloizou & Terquem, 2010) and HD 82943 (Beaugé et al., 2008) may be. Of imaged systems, dynamical models suggest that the 4-planet HR 8799 is plausibly in a double Laplace resonance, with periods of planets e,d,c,b in the (possible) ratio 1:2:4:8 (Goździewski & Migaszewski, 2014). A small number of Kepler multi-transiting systems, including Kepler–60, Kepler–79 and Kepler–80, may be in or near Laplace-like resonances (§6.30.4).

Numerical simulations of capture into Laplace resonance due to gas-driven migration were performed, for different mass ratios and drag parameters, by Libert &

Tsiganis (2011a,b). Various other models, illustrating their complex dynamical behaviour, and including non-planar configurations, have been described (e.g. Libert & Tsiganis, 2011a,b; Quillen, 2011; Lithwick & Wu, 2012; Batygin & Morbidelli, 2013b; Papaloizou, 2015; Goździewski et al., 2016).

**1:1 resonance** There are no known exoplanets or exomoons in the 1:1 (Trojan-like) resonance. The phenomenon, classes of 1:1 resonance, and detectability with Kepler, are considered in Section 6.21. Trojans in the solar system are described in Section 12.5.11.

**Retrograde resonance** The possibility of retrograde resonance has been considered, along with possible formation models, for HD 73526 (Gayon & Bois, 2008a). Further investigations for the planar problem, and in the vicinity of the main (2:1, 1:1, 1:2) retrograde resonances, have nonetheless demonstrated their stability (Morais & Giuppone, 2012; Morais & Namouni, 2013).

**The 4:3 resonance** While convergent migration can lead to capture into the first-order (widely-spaced) 2:1 or 3:1 resonances, more closely-spaced resonances (such as 3:2) are more problematic (e.g. Rein et al., 2010). This is because planets initially formed far apart must somehow migrate *through* the more widely-spaced outer resonances. To avoid appealing to finely-tuned initial conditions then requires relatively high inward migration rates (e.g. Rein et al., 2010; Ogiwara & Kobayashi, 2013), e.g. as found in type III migration (§10.10.2).

The more closely spaced 4:3 resonance is indicated for some systems, notably the radial velocity discovery HD 200964 (Johnson et al., 2011b; Wittenmyer et al., 2012b; Rein et al., 2012; Tadeu dos Santos et al., 2015; Mía & Kushvah, 2016). Tadeu dos Santos et al. (2015) found that only a thin flat protoplanetary disk allows embryo-sized planets to reach this configuration.

Four 4:3 transiting systems have been suggested: Kepler–105, Kepler–181, Kepler–226, and Kepler–232. Difficulties in modeling such systems, even with convergent migration, are detailed by Rein et al. (2012).

**Other formation scenarios** Other formation scenarios for the 4:3 resonance include (Rein et al., 2012): (a) formation from growing embryos with 4:3 period ratios (for which lower masses correspond to lower mutual interactions) followed by co-migration; (b) direct capture following planet–planet scattering (Chatterjee et al., 2008; Raymond et al., 2008a), a low-probability outcome augmented with gas disk damping (e.g. Matsumura et al., 2010b; Moeckel & Armitage, 2012); (c) *chaotic migration*, in which continued inward migration in a 3:2 resonance leads to increasing eccentricities and chaotic scattering into the 4:3 resonance regime; (d) breaking of a resonant chain initially involving at least three planets, which are created in some planet–disk simulations (e.g. Cresswell & Nelson, 2009).

**Solar system 4:3 resonances** In the solar system, Titan and Hyperion are in a 4:3 mean motion resonance (Taylor, 1984; Thomas et al., 2007). With a mass  $10^{-5}$  that of Titan, Hyperion



effectively acts as a ‘test particle’ with negligible effect on Titan’s orbit, and the stable resonance is dominated by a single term in the disturbing function (Colombo et al., 1974; Bevilacqua et al., 1980; Stellmacher, 1999; Beaugé et al., 2006). Bevilacqua et al. (1980) suggested that Hyperion formed at its present location as a result of the relative velocities of surviving planetesimals allowing for coagulation, while Beaugé et al. (2006) suggested that the two bodies were captured into resonance through smooth differential tidal migration across a chaotic zone.

Other 4:3 resonances in the solar system include the asteroid 279 Thule, part of the Thule dynamic group, which is in a 4:3 resonance with Jupiter; others are tabulated by Barucci et al. (2008b, p49). None directly correspond to a configuration comprising two massive planets, for which multiple terms in the disturbing function must be considered, and in which stable libration zones are not as well characterised.

**4:1 resonance and star-grazing orbits** In the solar system, some asteroids are perturbed into Sun-impacting orbits (e.g. Farinella et al., 1994). Mean motion resonances with Jupiter, and the  $\nu_6$  secular resonance with Saturn, were identified by Gladman et al. (1997) as the main mechanisms exciting their eccentricities to large values, far more effectively than planetary encounters. Comets from the Oort cloud are also driven into high-eccentricity Sun-grazing orbits (Marsden, 1967).

The collision of small bodies with the central star is not restricted to the solar system. The elemental pollution of white dwarf photospheres (§8.9.4), and the transient spectroscopic signatures of young stars like  $\beta$  Pic (box, page 282) provide growing evidence that extrasolar planetesimals can also attain extreme orbital eccentricities and fall into their parent stars.

Pichierri et al. (2017) showed that the 4:1 mean motion resonance with a moderately eccentric ( $e \lesssim 0.1$ ) planet is the most powerful in exciting planetesimal eccentricities from nearly circular orbits to star-grazing ones.

**Other mean motion resonance studies** Numerous other investigations have been made into the 2:1 and higher-order mean motion resonances.

Studies of the 2:1 resonance include their formation, ages, 3d resonances, stability, and long-term evolution (e.g. Zhang et al., 2010; Koriski & Zucker, 2011; Podlowska-Gaca & Szuszkiewicz, 2011; Antoniadou & Voyatzis, 2013; Batygin & Morbidelli, 2013a; Deck et al., 2013; Giuppone et al., 2013; Ketchum et al., 2013; Mardling, 2013; Teyssandier & Terquem, 2014; Zhang et al., 2014b; Horedt, 2015; André & Papaloizou, 2016; Wang & Malhotra, 2017). Amongst these, Koriski & Zucker (2011) found that systems with 2:1 commensurability are in general younger than others, with a possible inference that the 2:1 resonance tends to be disrupted after a few Gyr.

Stable orbits can exist, or be excited, in non-planar configurations with  $\Delta i$  up to  $50 - 60^\circ$  (Antoniadou & Voyatzis, 2013, 2014; Teyssandier & Terquem, 2014). Elliptical (aligned) orbits can remain stable even when the apocentre of the inner is larger than the pericentre of the outer (Giuppone et al., 2013).

Ketchum et al. (2013) found a complicated phenomenon, termed *nodding*, in which the resonance angle librates for several cycles, circulates for one or more cycles, and then re-enters libration. Often occurring when a small body is in external resonance with a larger, it could be important in interpreting transit timing variations, where the existence of a small body can be inferred through its effects on a larger transiting planet: in a nodding system, both the amplitude and frequency of the transit timing variations would be time dependent.

The dynamics of higher resonance orbits have been variously studied (e.g. Antoniadou & Voyatzis, 2014; Horedt, 2015). Simulations by Zhang et al. (2014b) found that multiple massive planets ( $M_p \gtrsim 0.8M_J$ ) tend to end up in a 2:1 resonance largely independent of the disk mass, but that low-mass planets ( $M_p \lesssim 30M_\oplus$ ) exceed 4:3 (i.e. including 2:1 and 3:2) only when the disk mass is small, suggesting that the observed dynamical architecture of most low-mass planet pairs was established late in the disk’s evolution, just before it was fully dispersed. Migration-induced formation and stability of the 9:7 resonance in the Kepler-29 system has also received specific attention (Migaszewski et al., 2017; Migaszewski, 2017).

**Evection resonance** The *evection resonance* describes a resonance between the Moon’s orbit around Earth and Earth’s orbit around the Sun. It occurs when the precession period of the lunar orbit equals the period of Earth’s orbit around the Sun, and causes the Moon’s ecliptic longitude to vary by  $\pm 1.27^\circ$  with a period of 31.8 d.

The ‘evection’ resonance (from the Latin for ‘carrying away’) arises from an approximately six-month periodicity variation of the eccentricity of the Moon’s orbit, and a libration of similar period in the position of the Moon’s perigee. It appears in discussions of the Moon’s origin (§12.3.3), where the angular momentum of the Earth–Moon system may have been modified by such a solar resonance: as the early Moon’s orbit expanded due to tidal interaction with the Earth, it could be captured into the evection resonance, which excites its orbital eccentricity and drains angular momentum from the system (Čuk & Stewart, 2012; Ward & Canup, 2013). The more significant the angular momentum loss, the wider the range of lunar-forming impact scenarios allowed.

Planets in circumbinary and multi-planet systems may experience evection resonance due to perturbations from a distant stellar companion, resulting in eccentricity excitation and disruption (Xu & Lai, 2016). It occurs when the apsidal precession frequency of the planet, driven by the quadrupole associated with the inner binary or other planets, matches the orbital frequency of the external companion.

## 10.9 Long-term stability

The derivation of Keplerian orbital elements which match the (radial velocity or transit) observables for a multi-planet system, as derived from either kinematic or dynamical fitting (§2.1.2), does not guarantee that the resulting orbits are stable over long periods of time. The formal best-fit solution might, for example, describe an unstable system which would swiftly disintegrate through ejection of one of the planets, or by causing two of the planets to collide. If such unstable behaviour is predicted to occur on short time scales, the solution is typically rejected as implausible. Conversely stability, even verified over long time periods, cannot prove the correctness of the solution, although it may be considered as a necessary condition for its validity.

An example is the two-planet system HD 82943, with an age of 2.9 Gyr. Although a genetic search algorithm proceeded from almost all initial values to the solution given by Mayor et al. (2004), Ferraz-Mello et al. (2005) showed that these published

**Titius–Bode law:** As noted by Johann Titius in 1766, and as reformulated and popularised by Johann Bode (1747–1826), the mean orbital distances of the six planets known at the time (Mercury to Saturn) are well approximated by

$$a = 0.4 + 0.3 (2)^i, \quad \text{where } i = -\infty, 0, 1, 2, 4, 5, \quad (10.40)$$

and  $a$  is the Sun–planet distance in au. The discovery of Uranus in 1781 at 19.2 au ( $i = 6$ ), and the first asteroid Ceres in 1801 at 2.8 au ( $i = 3$ ) were considered as predictions confirming an underlying structural law of the solar system. As a ‘law’, however, it has two shortcomings: it has, currently, no unequivocal physical basis (although see, e.g. Graner & Dubrulle, 1994; Dubrulle & Graner, 1994), and it has too many exceptions (notably the presence of Neptune, and the absence of planets between Mercury and Venus). The topic has nevertheless generated considerable debate (Nieto, 1972), which continues to the present, both in numerical and dynamical form (e.g. Lynch, 2003; Neslušan, 2004; Bass & del Popolo, 2005; Ortiz et al., 2007; Bohr & Olsen, 2010), or perhaps as the ‘*psychological tendency to find patterns where none exist*’ (Newman et al., 1994).

Murray & Dermott (2000, Section 1.5) assessed its significance by applying a two-parameter geometric progression to the major satellites of Uranus (Miranda to Oberon), as a distinct instance of orbital periods also displaying a number of simple numerical relationships. Although generating excellent numerical fits, their Monte Carlo analysis demonstrated that almost any period distribution would fit a Titius–Bode-type law equally well. They concluded that ‘*There is no compelling evidence that the Uranian satellite system is obeying any relation similar to the Titius–Bode law beyond what would be expected by chance. This leads us to suggest that the ‘law’ as applied to other systems, including the planets themselves, is also without significance.*’

Hayes & Tremaine (1998) made a similar statistical analysis for the solar system, and concluded that the law’s significance is simply that stable planetary systems tend to be regularly spaced; they suggested that the conclusion could be strengthened by more rigorous rejection of unstable planetary systems based on long-term orbit integration.

Multiple exoplanet systems have opened an extensive panorama for further conjecture (Poveda & Lara, 2008; Kotliarov, 2008, 2009; Panov, 2009; Chang, 2010; Flores-Gutiérrez & García-Guerra, 2011; Cuntz, 2012; Bovaird & Lineweaver, 2013; Migaszewski et al., 2013; Huang & Bakos, 2014; Smirnov, 2015; Geroyannis, 2015; Aschwanden, 2018). For example, Poveda & Lara (2008) made a Titius–Bode type fit to the five planets orbiting 55 Cnc. They predict that a further planet with  $a \approx 2.08$  au lies in the gap between  $a = 0.78 - 5.77$  au (evident in Figure 2.38), and possibly another at  $a \approx 15.3$ . A critique of this analysis is given by Kotliarov (2009), while a further assessment for the same system, supported by formation and stability analyses, was made by Cuntz (2012). To date, such ‘missing’ planets predicted to populate the 55 Cnc system have not been confirmed.

The Kepler multiple transiting systems have also been considered explicitly. For 20 systems with at least four planets within 0.5 au, Migaszewski et al. (2013) found that at least half, including Kepler–33, present linear ordering of the form  $a(n) = a_1 + (n - 1)\Delta a$ . They attribute this to multiple chains of mean motion resonances between adjacent planets, arising from planet–disk interactions and convergent migration at early evolutionary stages (see also Migaszewski, 2016). Bovaird & Lineweaver (2013) found that the majority of systems with at least four planets adhere to a generalised Titius–Bode relation to a greater extent than in the solar system, and used it to predict 141 additional planets in 68 systems. With 3.5 yr of Kepler data, Huang & Bakos (2014) searched for 97 of these predictions, yielding null results for the majority, and further questioning the relation’s predictive power. Further predictions were made by Bovaird et al. (2015).

An alternative structural law discussed by Kotliarov (2008), which he attributes to Butusov (1973), is related to symmetry. It is similarly phenomenological but claims fewer exceptions. It can be expressed as

$$a_Z^2 = a_{Z+k} \times a_{Z-k}, \quad (10.41)$$

where  $a$  is the star–planet distance, and  $Z$  is the planet defining the centre of symmetry, with  $k \in \{1, 2, \dots, Z - 1\}$ . Applied to the solar system, it implies that there is a Jovian symmetry to planetary distances, counting Jupiter as  $k = 6$  with Ceres as  $k = 5$ . Applied to 55 Cnc, Kotliarov (2008) predicts planets at different locations to Poveda & Lara (2008), viz. at  $a \approx 2.5$  and  $a \approx 16.1$ .

**Newcomb–Benford law:** a somewhat related mathematical curiosity is the discovery by astronomer-mathematician Simon Newcomb (1881), and rediscovered by Frank Benford in 1938 and generally known as Benford’s Law (in accordance with Stigler’s ‘law of eponymy’, which asserts that no scientific discovery is named after its original discoverer), that in many collections of numbers, such as mathematical tables and naturally occurring data, the leading digits are not uniformly distributed, but are heavily skewed toward smaller values. In its most common form, the special case of the first significant decimal (base-10) digits, it posits  $\text{Prob}(D_1 = d_1) = \log_{10}(1 + d_1^{-1})$ , for all  $d = 1, 2, \dots, 9$ , and where  $D_1$  denotes the first significant digit. There is a substantial mathematical literature (Berger & Hill, 2011), with practical applications in identifying suspicious tax returns, voter fraud, and altered digital images. In astronomy, it has been applied to the distances of galaxies and stars (Alexopoulos & Leontsinis, 2014). Shukla et al. (2017) suggest that some (but not all) Kepler planet properties, such as  $M_p$ ,  $a$ , and  $P$ , also follow this distribution. The ‘law’ presumably reflects some statistical property of the underlying distributions.

orbits correspond to a fate in which one of the planets is expelled, or collides with the star, in less than 100 000 yr.

### 10.9.1 Secular theory

Mutual perturbations cause the Keplerian orbital elements to change on time scales which can be short compared with a system’s age. Numerical integration is

therefore often part of the orbit-fitting process, because it can exclude ranges of masses and orbit elements that may be consistent with observational data, but inconsistent with long-term stability. While numerical integration can better characterise long-term behaviour, secular theory provides a convenient way of characterising a system’s (current) dynamical state.

Keplerian orbital elements are constants of integration in the two-body problem, but they are not constant when multiple planets interact. Mutual interactions are enhanced by orbital resonances, but even in their absence, *secular interactions*, in which planets exchange angular momentum (so that eccentricities and longitudes of pericentre vary periodically), can be of key dynamical relevance. For small  $e$ , and in the absence of mean motion resonances, the analytical solutions of a secular analysis represent the system better than the Keplerian elements.

*Classical secular theory* involves averaging the disturbing force at a planet due to every other planet over the planets' orbital periods (Brouwer & Clemence, 1961; Murray & Dermott, 2000). The remaining disturbing potential is then used to calculate changes in the Keplerian elements over time. In effect, the gravitational interactions are computed as if each planet's mass is distributed (suitably weighted) along its Keplerian orbit. In practice, the disturbing potential is expanded as a Fourier series, with terms that explicitly contain orbital longitudes in the arguments of the sines or cosines (as in the case of mean motion resonance) are ignored.

**Functional form** The variation equations assume a simple linear form if the Keplerian elements  $e$  and  $\tilde{\omega}$  (§2.1.1) are replaced by  $k_i = e_i \cos \tilde{\omega}$ ,  $h_i = e_i \sin \tilde{\omega}$ . Lagrange's equations for the perturbations in an  $N$ -planet system are then

$$\dot{k}_i = - \sum_{j=1}^N A_{ij} h_j \quad ; \quad \dot{h}_i = + \sum_{j=1}^N A_{ij} k_j, \quad (10.42)$$

where the matrix  $A$  depends on  $M_*$ ,  $M_{p_i}$  and  $a_{p_i}$ , and can include other precession terms, e.g. due to general relativity or stellar oblateness (§6.19.4). The solution to these first-order linear differential equations is a sum of eigenmodes

$$k_i = \sum_{m=1}^N E_m V_{m_i} \cos(g_m t + \delta_m) \quad (10.43)$$

$$h_i = \sum_{m=1}^N E_m V_{m_i} \sin(g_m t + \delta_m), \quad (10.44)$$

where  $V_m$  are the eigenvectors of  $A$ , and  $g_m$  are the corresponding eigenfrequencies.  $E_m$  and  $\delta_m$  are the constants of integration, while the Keplerian elements vary with time.

For each planet, the vector  $(h_i, k_i)$  is the sum of  $N$  component vectors, each corresponding to a particular eigenmode, and rotating in  $(h, k)$  space at an angular velocity  $g_m$ . For a given eigenmode, the component vectors contributing to each planet are all either parallel or anti-parallel. As a result, if only one of the eigenmodes is non-negligible, all the planets' directions of pericentre would be aligned (if the signs of  $V_{m_i}$  are the same) or anti-aligned (if opposite). Equivalently, the planets' major axes (lines of apsides) are aligned or anti-aligned. Further details of secular behaviour, including how it describes libration or circulation about the (anti-)aligned axes, are given in e.g., Murray & Dermott (2000); Chiang & Murray (2002); Barnes & Greenberg (2006b,c); Greenberg & van Laerhoven (2012).

The eigenmodes can help identify tidal effects, planet-planet scattering, dynamical coupling, and packing density (e.g. Migaszewski & Goździewski, 2008; Veras & Ford, 2010; Van

Laerhoven & Greenberg, 2012). A case study for the 5-planet system 55 Cnc is didactically presented by Van Laerhoven & Greenberg (2012). Many other multiple systems have been similarly characterised (see Appendix C).

Higher-order expansions of the disturbing forces yield expressions that are valid for arbitrary  $e$  and  $i$ , or for systems closer to mean motion resonance (e.g. Laskar & Boué, 2010; Libert & Sansottera, 2013; Naoz et al., 2013a; Veras & Evans, 2013b; Boué & Fabrycky, 2014a,b; Campo & Docobo, 2014; Georgakarakos et al., 2016; Read & Wyatt, 2016).

### 10.9.2 Stability

Dynamical stability as applied to exoplanet systems can carry at least two somewhat different meanings (Barnes & Greenberg, 2006c; Barnes, 2008): *Lagrange stability* in which no planet is ever ejected and the semi-major axes remain bounded for all time; and *Hill stability* or *hierarchical stability* in which the outermost planet might escape but not the inner, implying that the ordering of the bodies remains constant (see accompanying box).<sup>5</sup>

**Time scales** Associated with the long-term outcome of a dynamically interacting system, Paardekooper et al. (2013) defined four different time scales that give an indication of how long a system might be stable:

- the *Lyapunov time scale* is a measure of how fast two nearby orbital solutions diverge. The measure is related to the concept of 'chaos' (§10.9.4);
- the *collision time scale* measures the time until the two planets have a close encounter or a physical collision;
- the *ejection time scale* measures the time until at least one planet becomes gravitationally unbound from the host star and leaves the systems, (a measure based simply on direct outcomes of N-body simulations). This measure is closely related to the collision time scale and Hill stability, although Hill stability is a sufficient but not necessary condition for stability (e.g. Deck et al., 2012). For example, for planetary systems of masses and densities comparable to Kepler-36 (Paardekooper et al., 2013), instability usually results in a physical collision rather than ejection of one of the planets;
- the *Lagrange time scale* is the time until one of the semi-major axes changes by more than 10%. The planets might be ejected after a drastic change in their orbital parameters, or the inner may collide with the star, or they may remain in a new stable configuration.

**Numerical methods** The development of efficient numerical methods for exploring parameter space, or for

<sup>5</sup>*Hierarchical* has also been used to describe exoplanet systems in which there is a significant ratio of their semi-major axes,  $a_1/a_2 \leq 0.3$  (Lee & Peale, 2002; Goździewski & Konacki, 2004; Wright, 2010). With these two distinct definitions, a hierarchical planetary system is not necessarily hierarchically stable. In multiple star terminology, hierarchical structuring describes orbits nested within significantly larger orbits.

**Hill radius and Hill stability:** The *Hill radius* is the radius within which the gravity of one object dominates that of other bodies in the system. For a planet in a circular orbit of radius  $r$ , its Hill radius depends on the planet and central star mass as (e.g. Hamilton & Burns, 1992)

$$R_H = r \left( \frac{M_p}{3M_\star} \right)^{1/3}. \quad (10.45)$$

The concept of *Hill stability* is based on the more precise construct of zero-velocity surfaces introduced by Hill (1878) in his treatment of the lunar motion, and has since been used extensively in analytical considerations of both the restricted three-body problem, and that of general three-body motions (e.g. Murray & Dermott, 2000; Veras & Armitage, 2004a; Donnison, 2006). Although, in general, it is only possible to follow such close encounters in detail by numerical orbit integration of all three masses, the concept of Hill stability provides analytic limits on the range of the system's orbital elements if it is to remain stable, i.e. avoiding either disruption, collision, or positional exchange.

The product  $L^2E$ , where  $E$  is the energy and  $L$  is the angular momentum of the system, controls the topology of the zero-velocity surfaces, and determines the regions of allowed motions since bodies may not cross the zero-velocity surfaces (Donnison, 2006). The system is considered to be *Hill stable* against disruption or exchange if  $L^2|E|$  is greater than the critical value for the corresponding three-body Hill surface defined by the position of the colinear Lagrange points. The condition is sufficient for stability, but is not necessary: exchange cannot occur if the condition is satisfied, but might not occur even if the condition is violated.

The theory was originally applied to co-planar systems in bound orbits. It has been extended to bound stellar systems with mutually inclined orbits (Szebehely & Zare, 1977; Marchal & Bozis, 1982), to the stability of planets on circular orbits (Gladman, 1993), to the case of planets with mutually inclined orbits (Veras & Armitage, 2004a; Donnison, 2009, 2010a; Grishin et al., 2017), to hypothetical compact planets in the CoRoT discovery space (Funk et al., 2010), to generalised Trojan-like orbits (Kovács, 2013), and to stable chaotic regions in proximity to the Hill limit (Marzari, 2014).

Conservative stability criteria based on multiples of their combined Hill radii are also constructed (e.g. Hayes & Tremaine, 1998; Cuntz & Yeager, 2009), although this is often too restrictive (Marzari, 2014).

Hill stable pairs may eventually manifest Lagrange instability (with the inner colliding with the star, or the outer escaping), but not within the main sequence lifetime for terrestrial mass planets (Veras & Mustill, 2013).

studying long-term orbit evolution, has been important in understanding the large-scale and long-term dynamics of the solar system. These tools are now routinely applied to studies of the stability and evolution of multiple planets (e.g. Barnes & Quinn, 2004). Of particular importance has been the use of *symplectic integrators*, developed for numerical integration of systems governed by Hamilton's equations within a symplectic geometry (box, page 513).

Wright et al. (2009b) describe their algorithmic approach to assessing system stability which proceeds as follows: orbits are assumed to be co-planar and edge-on, with stellar masses established independently (Takeda et al., 2007a). The radial velocity parameters are converted into initial conditions in a Jacobi coordinate system (Lissauer & Rivera, 2001; Lee & Peale, 2003). Systems are then integrated for  $\geq 10^8$  yr using the hybrid integrator Mercury (Chambers, 1999). Solutions are classified as unstable if two planets are predicted to collide, or if a planet falls onto the star ( $d < 0.005$  au), or if it is ejected from the system ( $d > 100$  au).

The effects of resonances and chaos can mean that stable and unstable solutions are only marginally separated in parameter space. The evolution of the system must therefore be explored for a range of parameters in the vicinity of the  $\chi^2$  minimum to ensure the solution's stability. HD 183263 is an example of a two-planet system where the  $\chi^2$  minimum falls close to a stability boundary, such that many solutions consistent with the data are unstable (Figure 10.31).

**Dynamical classification** Barnes (2008) has classified multiple planet systems according to the type of dynamical interaction that dominates. A system is considered *tidally dominated* if the semi-major axis  $a \lesssim 0.1$  au (Rasio et al., 1996), *resonantly dominated* if one or more resonant arguments librates, and *secularly dominated* otherwise (as is the case for the solar system gas giants).

The general dynamical properties of multiple exoplanet systems, and a summary of their dynamical state, is given by Barnes (2008), where a tabulation provides, for each pair: the resonance, if applicable; the apsidal motion, viz. circulation or (anti-)aligned libration; proximity to the apsidal separatrix (Barnes & Greenberg, 2006b); proximity to the Hill stability boundary (Barnes & Greenberg, 2007b); and whether the orbit evolution is dominated by tidal, resonant, or secular interactions.

Of the 34 planet pairs classified by Barnes (2008), the numbers in each category were 10, 8 and 16 respectively.

**Angular momentum deficit** Another measure of a system's dynamical stability, and one which can be more easily estimated, is based on its *angular momentum deficit*, AMD. This is the difference between the norm of the angular momentum of an  $n$ -body system, and the norm of the angular momentum of a co-planar and circular system with the same semi-major axes (Laskar & Petit, 2017, eqn 11)

$$C = \sum_{k=1}^n \Lambda_k \left( 1 - \sqrt{1 - e_k^2} \cos i_k \right), \quad (10.46)$$

where  $e_k$  and  $i_k$  are the orbit eccentricities and inclinations, and  $\Lambda_k = m_k \sqrt{GM_\star a_k}$ .

The angular momentum deficit provides a measure of orbital excitation and the potential for close encoun-

**Symplectic integrators and the N-body problem:** N-body simulations are used in many areas of astronomy, including studies of the formation and evolution of planetary systems, to probe the behaviour of many ‘particles’ interacting (primarily) under the influence of gravity. An overview, including the principal algorithmic ‘stepping stones’, and the development of the (public domain) routines NBODY1–NBODY6, is given by Aarseth (1999). Applied to the long-term behaviour and stability of exoplanet orbits, a crucial feature is not so much the number of particles that can be treated, but rather the accuracy of the orbits over long time intervals, for which long-term integration requires conservation of the integrals of motion to high precision.

In describing the motion of dynamical systems, a sequence of deterministic algebraic steps are executed to follow its evolution from an initial to some final state. Such *algebraic mappings* include the classical (non-symplectic) fourth-order Runge–Kutta iteration for the approximate solution of ordinary differential equations (e.g. Press et al., 2007). These conventional integrators carry the penalty of ‘numerical dissipation’, which results in a secular change of energy even in a conservative system. The consequence is that positional errors then grow quadratically with time.

*Symplectic integrators* were developed as a specific numerical integration for the solution of Hamilton’s equations, i.e. for particular problems occurring in classical mechanics within the appropriate (symplectic) geometry. Wisdom & Holman (1991), who called their method an ‘N-body map’, and Kinoshita et al. (1991), who called their method a ‘modified symplectic integrator’, developed such a mapping for the N-body problem, inspired by efforts to understand the very long-term stability of solar system orbits. The Hamiltonian is split into an unperturbed Keplerian part, and an additional contribution describing smaller mutual gravitational interactions; each part can then be integrated separately. Separation involves the introduction of a new system of variables transformed from standard Cartesian to Jacobi coordinates, in which (hierarchically) the masses of bodies  $m_i$  and  $m_j$  are replaced by a virtual body of mass  $m_i + m_j$ , and their individual positions replaced by their relative positions and their centre of mass. For a step-by-step description see, e.g., Murray & Dermott (2000, Section 9.5.4).

The defining feature of symplectic integrators is that they preserve symplecticity; in practice, this means that the total energy and angular momentum do not exhibit secular evolution, and positional errors grow only linearly with time. Time-reversal symmetry is not, however, necessarily explicitly respected (Rein & Tamayo, 2018).

Use of symplectic integrators for the N-body problem is widespread. Higher-order gravitational effects (e.g. quadrupole moments, general relativity, and stellar mass loss) can be included. Other developments include reducing long-term errors (Saha & Tremaine, 1992), introducing separate time steps for each body (Saha & Tremaine, 1994), improved treatment of close approaches (Levison & Duncan, 1994), allowing for dissipative terms such as drag, inelastic collisions, radiation forces, and tidal distortions (Malhotra, 1994), special considerations for binary star systems (Chambers et al., 2002), allowing for radial zones with distinct time steps (McNeil & Nelson, 2009), adaptive time-stepping (Kaib et al., 2011a), shearing sheets for disk systems (Rein & Tremaine, 2011), distinguishing between regular and chaotic orbits (Libert et al., 2011), the treatment of secular numerical error (Ito & Tanikawa, 2012), use of second-order variational equations (Rein & Tamayo, 2016), and considerations for exact reproducibility (Rein & Tamayo, 2017).

Symplectic integrators used for exoplanet studies (for introductions see, e.g. Barnes, 2008; McNeil & Nelson, 2009; Rein & Spiegel, 2015) include, chronologically, SWIFT (Levison & Duncan, 1994), SyMBA, a multi-time step integrator (Duncan et al., 1998), Mercury, a the hybrid integrator (Chambers, 1999), SABA4 (Laskar & Robutel, 2001), HNBody (Rauch & Hamilton, 2002, 2012), NBSymple (Capuzzo-Dolcetta et al., 2011), SEI and SEKI, optimised for disks and planetary rings by allowing for non-conservative (radiation) forces (Rein & Tremaine, 2011), REBOUND, with 3 different integrators (Rein & Liu, 2012), GENGA, a GPU-based hybrid integrator handling close encounters (Elser et al., 2013; Grimm & Stadel, 2014), Mercury-T, an addition to Mercury, taking into account tides, general relativity and rotation-induced flattening in multi-planet systems (Bolmont et al., 2015), WHFast (Rein & Tamayo, 2015), HB15, with an emphasis on accuracy in close encounters (Hernandez, 2016), and JANUS, respecting time-reversal symmetry (Rein & Tamayo, 2018).

Non-symplectic (symmetric multi-step) integrators can nevertheless still offer advantages in specific situations, including the treatment of adaptive time steps, systems of particles of comparable mass, and the presence of non-conservative forces (Quinlan & Tremaine, 1990). IAS15 has been developed specifically for exoplanet applications (Rein & Spiegel, 2015). The use of graphics processing units (GPUs) in accelerating N-body computations has been another important area of computational advance (e.g. Bédorf et al., 2012; Nitadori & Aarseth, 2012; Dindar et al., 2013; Elser et al., 2013; Grimm & Stadel, 2014).

ters, and decreases during inelastic collisions, so accounting for the gain of stability of a lower multiplicity systems (Laskar, 1997, 2000; Hernández-Mena & Benet, 2011; Laskar & Petit, 2017). Such behaviour is seen in N-body simulations of planetary formation (e.g. Chambers, 2001; Raymond et al., 2006c), as well as reflecting the simple model of embryo accretion of Laskar (2000) in which N-body dynamics is interpreted as the exchange of AMD. The AMD-stability criterion has also been extended to include cases of mean motion resonances (Petit et al., 2017).

Laskar & Petit (2017) derived the conditions under which angular momentum deficit precludes collisions,

and conjectured that, in the absence of short-period resonances, AMD-stability ensures the system’s long-term stability. They applied these criteria to 131 multi-planet systems with well-determined orbits, classifying them as strong AMD-stable, weak AMD-stable, and AMD-unstable (including systems experiencing mean motion resonances, for which more detailed dynamical modeling is needed to assess stability). Since the criterion depends on mass ratios, it does not depend on the  $M_p \sin i$  degeneracy in radial velocity measurements.

Hierarchically AMD-stable systems are those where the outer part is AMD-stable although the entire system is not. The solar system is an example, for which the in-

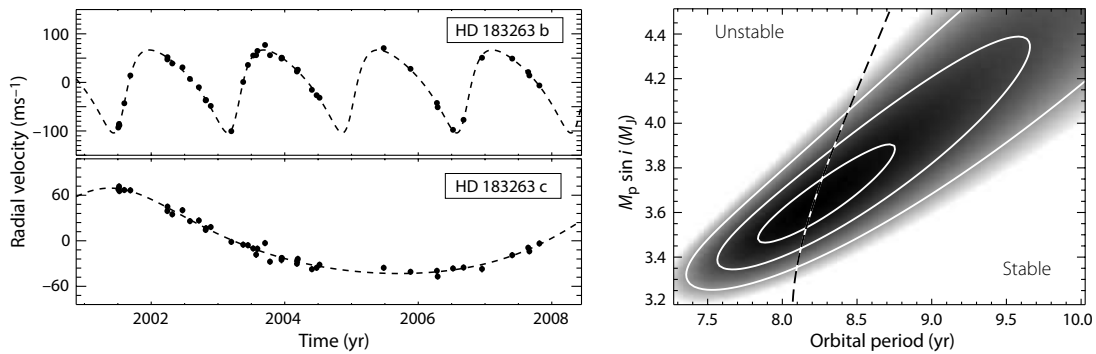


Figure 10.31: HD 183263 observed at the Keck Observatory. Left: the inner planet (b) with  $P = 1.7$  yr,  $M_p \sin i = 3.7 M_J$  (top) and the outer planet (c) with  $P \sim 8$  yr,  $M_p \sin i = 3.6 M_J$  (bottom); in each case, the effect of the other planet has been removed. Right: contours of  $\chi^2$ , with solid contour lines increasing by factors 1, 4, 9 from the minimum. The dashed curve divides stable from unstable orbital solutions, as determined from an ensemble of  $N$ -body integrations. From Wright et al. (2009b, Figures 2–3), by permission of IOP Publishing/AAS.

ner solar system is chaotic (and not AMD-stable), while the outer solar system is largely quasi-periodic (Laskar, 1997). When AMD exchange occurs between the outer and inner solar system, the inner system becomes unstable, and can lose one or several planets. Although long-term integrations show that the inner system has a probability of becoming unstable of only 1% over 5 Gyr, this nonetheless demonstrates that an *a priori* unstable system can continue to exist in its current form. Laskar & Petit (2017) identified four similar systems: 55 Cnc, GJ 676A, HD 10180, and HD 141399 (cf. their Figure 9).

### 10.9.3 Dynamical packing

Many planetary systems are found to be dynamically ‘full’, in the sense that no additional companions can survive in between the observed planets, with most pairs of planets lying close to dynamical instability. This finding has led to the *packed planetary systems* hypothesis (Barnes & Quinn, 2004; Barnes & Raymond, 2004; Raymond & Barnes, 2005; Raymond et al., 2006a), and to general studies of orbital stability for systems that are closely spaced (Smith & Lissauer, 2009).

Various searches have been made for regions of Lagrange stability between pairs of planets that are more widely separated (Menou & Tabachnik, 2003; Dvorak et al., 2003b; Barnes & Raymond, 2004; Funk et al., 2004; Raymond & Barnes, 2005; Raymond et al., 2006a; Rivera & Haghighipour, 2007; Barnes & Greenberg, 2007b). In a few systems (for example, in HD 74156 b–c, HD 38529 b–c, and 55 Cnc c–d) there are gaps which are large enough to support additional Saturn-mass planets.

A new Saturn-mass planet in the HD 74156 system was reported by Bean et al. (2008b). It lies between planets b and c, close to the ‘empty’ stable orbit identified in the numerical simulations of Raymond & Barnes (2005). Similarly, a new Jupiter-mass planet in the  $\nu$  And system

(§2.12.3), planet e, was reported by Curiel et al. (2011), its orbit coinciding with an island of stability reported by Rivera & Haghighipour (2007).

Long-term dynamical studies of the solar system (§12.4) show that, in its outer parts, it is not only very stable but also dynamically full (Gladman & Duncan, 1990; Holman & Wisdom, 1993; Levison & Duncan, 1993). The inner region is significantly less stable, but is also dynamically full (Sussman & Wisdom, 1992; Laskar, 1994).

### 10.9.4 Chaotic orbits

An appreciation of the role of chaos has been an important development in the understanding of the solar system’s dynamical evolution (Wisdom, 1987a,b; Murray, 1998; Murray & Holman, 2001), and the same principles are directly applicable to the study of multiple exoplanet orbits. In the solar system, chaos is apparent in phenomena such as the 3:1 Kirkwood gap (Wisdom, 1983), the tumbling motion of Saturn’s moon Hyperion (Wisdom et al., 1984), and in elements of Pluto’s orbit (Sussman & Wisdom, 1988), and has been attributed to result from overlapping resonances (Lecar et al., 2001).

Given a knowledge of initial conditions and forces acting upon it, the evolution of a conservative  $N$ -body system follows deterministic laws, in principle allowing the calculation of its past and future state with arbitrary accuracy. An orbit is loosely described as *chaotic* (as opposed to *regular*) if its dynamical state at some future time is sensitively dependent on the initial conditions.

Chaotic orbital motion may only become apparent after long times, for example only after  $10^8$  yr in the case of Pluto (Sussman & Wisdom, 1988), so that efficient methods of orbit integration, and procedures to quantify chaotic motion, are pivotal to its consideration.

**Lyapunov time** The tendency to chaos can be quantified. The divergence of two trajectories in *phase space*

**Dimensionality of space:** That physical space has three dimensions (at least on a macroscopic scale) appears self-evident. Yet dimensionality is considered one of the fundamental parameters of physics (e.g., one of six selected by Rees 2000), and various authors have asked the question: why three? Ehrenfest (1917) showed that the stability of  $N$ -dimensional two-body planetary systems (as well as atoms) places a strong constraint, favouring  $N = 3$ . This was confirmed within the framework of general relativity by Tangherlini (1963), and of quantum mechanics by Gurevich & Mostepanenko (1971), where direct experimental measurement has been proposed (Caruso & Moreira Xavier, 2012). Biological arguments for  $N = 3$  based on topology were considered by Whitrow (1955).

Barrow & Tipler (1986, pp258–276) consider dimensionality in the context of the anthropic principle (see box, page 630). Of relevance for the long-term stability of planet orbits, they conclude: *‘The inverse square law of force that is dictated by the three dimensions of space is unique in that it allows the local gravitational field... to be evaluated independently of the structure of the entire Universe beyond its outer boundary. Without this remarkable safeguard our local world would be at the mercy of changes in the gravitational field far away across our Galaxy and beyond.’*

(the six-dimensional mathematical space defined by its position and velocity vectors) with initial infinitesimal vectorial separation  $\delta\mathbf{Z}_0$  can be written

$$|\delta\mathbf{Z}(t)| \approx e^{\Lambda t} |\delta\mathbf{Z}_0|, \quad (10.47)$$

where  $\Lambda$  is the *Lyapunov exponent*, or Lyapunov characteristic exponent (e.g. Lyapunov, 1892; Hénon & Heiles, 1964; Oseledec, 1968; Lichtenberg & Leiberman, 1983; Froeschlé, 1984; Murray & Dermott, 2000). The rate of separation can be different for different orientations of the initial separation vector, and the number of Lyapunov exponents is therefore given by the dimensionality of the phase space. Reference is normally made only to the *maximal Lyapunov exponent* constructed from Equation 10.47

$$\Lambda = \lim_{t \rightarrow \infty} \frac{1}{t} \ln \frac{|\delta\mathbf{Z}(t)|}{|\delta\mathbf{Z}_0|}, \quad (10.48)$$

since that dictates the predictability of the system.

The evolution of  $\Lambda$ , determined from numerical integration of the orbits, typically shows a marked difference between regular and chaotic behaviour: regular orbits tend to a slope of  $-1$  in  $\log \Lambda$  versus  $\log t$ , and chaotic orbits tend to some positive value of  $\Lambda$ . The corresponding *Lyapunov time*, the time taken for the displacement to increase by a factor  $e$ , is given by  $1/\Lambda$ .

As specific examples, both Sussman & Wisdom (1992) and Laskar (1996) found that the inner solar system is chaotic, with a Lyapunov time of 5 Myr. The chaotic behaviour is attributed to two secular resonances, one related to the perihelia and nodes of Mars and Earth, the other related to those of Mercury, Venus and Jupiter. As a consequence, an error of only 15 m in

the Earth’s initial position leads to an error of 150 m after 10 Myr, growing to  $150 \times 10^6$  km after 100 Myr. It is thus conceivable to construct solar system ephemerides over 10 Myr, but practically impossible to predict planetary motions beyond 100 Myr. Similarly, the orbit of Pluto is chaotic, with a Lyapunov time of 20 Myr (Sussman & Wisdom, 1988), although its small mass means that its chaotic orbit has negligible consequences for the solar system planets. The orbit of Comet Halley, also chaotic, has a Lyapunov time of only  $\sim 300$  yr (Muñoz-Gutiérrez et al., 2015; Boekholt et al., 2016).

A system can be stable, at the same time as being chaotic, so long as its future evolution is restricted to certain bounds. The absence of a clear pattern in the orbital elements with time does not in itself imply that the orbit is chaotic, but neither does a chaotic orbit necessarily imply that the system will be catastrophically disrupted. Intermittent chaotic behaviour punctuating long periods of ‘stagnant motion’ is found, for example, in many three-planet systems (Shikita et al., 2010). Transition from chaotic to a quasi-periodic states may occur due to dissipative interactions in young planetary systems (Batygin & Morbidelli, 2011), and examples have been identified in the case of the long-term orbit of Mercury (Batygin et al., 2015b).

There is no general relation, for example, between the Lyapunov time and the time when a macroscopic system instability occurs (Soper et al., 1990; Lecar et al., 2001; Michtchenko & Ferraz-Mello, 2001b). Neither does the Lyapunov time provide a measure of the ‘degree’ of chaos, since a system either is, or is not, chaotic.

**Indicators of chaos** Practical methods for rapidly distinguishing regular from chaotic orbits include various types of frequency analysis (e.g. Laskar, 1990, 1993) and various types of fast Lyapunov indicators (e.g. Froeschlé et al., 1997a; Guzzo et al., 2002; Mestre et al., 2011).

For the four-planet system  $\mu$  Ara, for example, Pepe et al. (2007) used SABA4 to integrate over 2000 yr with a step size of 0.02 yr. Orbit stability was measured using a simplified frequency analysis based on the mean motion of a given planet over two consecutive intervals of  $t = 1000$  yr,  $n_p$  and  $n'_p$ . They used the parameter

$$D = \frac{|n_p - n'_p|}{t} \quad \text{deg yr}^{-1} \quad (10.49)$$

to provide a simplified measure of the orbit’s evolution, with values close to zero implying a regular solution, and with larger values indicating more chaotic motion.

Within the class of fast chaos indicators is MEGNO (Mean Exponential Growth of Nearby Orbits; Cincotta & Simó, 2000), originally developed to study the global dynamics of non-axisymmetric galactic potentials. It has been used to investigate stability and resonant structure in a number of multiple exoplanet systems, and typically performs over a relatively small number ( $\sim 10^4$ )

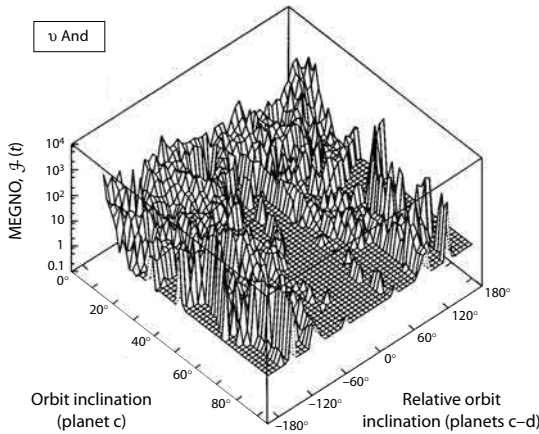


Figure 10.32: Stability analysis for  $v$  And with MEGNO, using orbit data from Butler et al. (1999). The parameter  $\bar{\mathcal{J}}$  (Equation 10.52) develops along the vertical axis, as a function of both the orbit inclination of planet c, and the relative inclinations of planets c and d. The flat areas indicate quasi-periodic zones, and the peaks indicate chaotic regions. From Goździewski et al. (2001, Figure 12), reproduced with permission © ESO.

of orbital periods of the outermost planet. Its essence is to amplify the effects of instability, such that signs of chaotic behaviour can be detected much earlier. This is seen by rewriting Equation 10.48 in integral form as

$$\Lambda = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T \frac{\delta \dot{\mathbf{Z}}(t)}{\delta \mathbf{Z}(t)} dt, \quad (10.50)$$

then introducing the time-amplified *mean exponential growth of nearby orbits*  $\mathcal{J}(T)$  (Cincotta & Simó, 2000, eqn 22) as

$$\mathcal{J}(T) \equiv \frac{2}{T} \int_0^T \frac{\delta \dot{\mathbf{Z}}(t)}{\delta \mathbf{Z}(t)} t dt, \quad (10.51)$$

with its evolving mean value

$$\bar{\mathcal{J}}(T) \equiv \frac{1}{T} \int_0^T \mathcal{J}(t) dt. \quad (10.52)$$

For regular orbits  $\bar{\mathcal{J}}(T) \rightarrow 2$ , while for chaotic orbits it grows, proportionally to the Lyapunov exponent, as  $\bar{\mathcal{J}} \rightarrow (\Lambda/2)T$ . Implementation requires integration of two differential equations in addition to the equations of motion (see also Rein & Tamayo, 2015, 2016). The analytical relation between MEGNO and the fast Lyapunov indicator is described by (Mestre et al., 2011).

Various multi-planet systems have been studied with MEGNO, including  $v$  And (Goździewski et al., 2001), HD 12661 (Goździewski, 2003b; Goździewski & Maciejewski, 2003), HD 37124 (Goździewski, 2003a; Goździewski et al., 2008a),  $\mu$  Ara (Bois et al., 2003; Goździewski et al., 2003, 2005a), HD 169830 (Goździewski & Konacki, 2004), the 5-planet 55 Cnc (Gayon et al., 2008), the possibly retrograde resonance

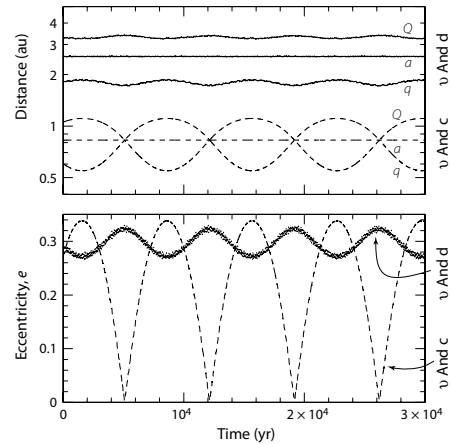


Figure 10.33: Secular evolution of the  $v$  And planetary system. Top: semi-major axes,  $a$  (central lines), pericentre,  $q$ , and apocentre,  $Q$ , for the outer planets, c and d. Bottom: evolution of the eccentricities. Both planet c (lower, dashed) and planet d (upper, dotted) have a significant eccentricity at present ( $t = 0$ ), although the eccentricity of c periodically returns to very small values near zero. From Ford et al. (2005, Figure 1), by permission from Nature/Springer/Macmillan Ltd, ©2005.

HD 73526 (Gayon & Bois, 2008a), HU Aqr (Goździewski et al., 2015), and the Laplace resonance Kepler-60 (Goździewski et al., 2016).

A related chaos-detection method is through the use of *relative Lyapunov indicators*, which measure the difference between the convergence of the finite time Lyapunov indicators to the maximal Lyapunov characteristic exponent of two initially very close orbits (Sándor et al., 2000, 2004; Rein & Tamayo, 2015). The method is considered to be very fast in determining the ordered or chaotic nature of individual orbits, even those with very small Lyapunov characteristic exponents, with results over a few hundred times the period of the longest orbit. Examination of the stability of various exoplanet systems using this indicator has been variously described (e.g. Érdi et al., 2004; Sándor et al., 2004, 2007b).

Another fast dynamical indicator REM, for ‘reversibility error method’, and based on a symplectic and time-reversible (symmetric) indicator, is described by (Panichi et al., 2017b), and applied to five resonant planetary systems.

**Stellar mass loss** Planetary orbits also evolve as the host star loses mass, a long-studied problem in solar system dynamics (e.g. Gylden, 1884; Jeans, 1924; Hadjidemetriou, 1963, 1966). This can lead to planet orbits becoming unstable or unbound.

**Effects of stellar mass loss** For single planets orbiting stars with constant mass-loss rate, the orbital semi-major axis grows, and the planet may become unbound (Veras et al., 2011b; Adams et al., 2013b). Effects of tidal dissipation have also been included (Adams & Bloch, 2013), as have Galactic tidal perturbations and stellar fly-bys (Veras et al., 2014). Widely-spaced



multi-planet systems evolve much like single planet systems. If the planets are sufficiently close that planet–planet interactions are important, the systems are generally chaotic, and planets can escape (Veras et al., 2011b; Veras & Tout, 2012; Adams et al., 2013b; Voyatzis et al., 2013; Veras, 2016b).

Mass loss in binary star systems can allow a planet to change their host star (Kratter & Perets, 2012; Moeckel & Veras, 2012; Perets & Kratter, 2012; Rahoma, 2016).

Time-dependent stellar mass-loss has also been considered (Adams et al., 2013b). For a 3-body solar system analogue comprising the Sun, Jupiter and Saturn, Adams et al. (2013b) found a chaotic system with Lyapunov time  $\Lambda^{-1} \sim 5 - 10$  Myr in the absence of mass loss, while the Lyapunov time decreases almost linearly with increasing mass-loss rate.

The related effect of stellar radiation pressure on a (small) body's surface has been considered by Xu & Xu (2013). Anisotropic mass loss, in both the T Tauri and post-main sequences phases, is considered by Veras et al. (2013a).

**Variation of gravitational constant** The problem of planetary orbits with stellar mass loss is analogous to that of time variation of  $G$ . For single planet systems (the pure two-body problem), the gravitational force depends only on the product  $GM_*$ , and the two problems are equivalent (e.g. Vinti, 1974).

**Mass loss beyond the main sequence** Long-term integrations have also studied the distant fate of planets due to mass loss from the dying Sun (Duncan & Lissauer, 1998; Veras & Wyatt, 2012). Earth is likely to be engulfed by the Sun, while planets in wider orbits may survive (box, page 414). Gas giants that escape engulfment are subject to continued evaporation, and can themselves experience significant mass loss (Bear & Soker, 2011b; Spiegel & Madhusudhan, 2012).

Planets orbiting more massive stars, which lose a larger fraction of their initial mass, are subject to possible engulfment during the planetary nebula phase, or may become unbound due to stellar mass loss alone (Villaver & Livio, 2007, 2009; Mustill & Villaver, 2012). Stellar mass loss can lead to unstable planetary systems surrounding post-main sequence white dwarfs (§8.9.1), with observational evidence for both white dwarf circumstellar disks and possibly planetary systems (§8.9.3), as well as 'polluted' atmospheres assumed to be signatures of accreted planetary-like bodies (box, page 416).

## 10.10 Orbital migration

### 10.10.1 Evidence for migration

A robust formation mechanism must explain not only the observed properties of the solar system, but also the exoplanet frequency and mass distribution, including their frequently large eccentricities.

Particular challenges are posed by the large number of 'close-in' planets with  $a \lesssim 0.2$  au, where high temperatures and relatively small amount of protostellar matter would preclude accretion *in situ* (Boss, 1995; Bodenheimer et al., 2000), and by planets with very large semi-major axes,  $a \gtrsim 100$  au, found from direct imaging (§7.10). Many can be at least partially explained by the effects of orbital migration (Baruteau & Masset, 2013).

Details of the specific orbits and other characteristics of hot Jupiters, and the constraints derived from them, is given in Section 10.7.1.

### 10.10.2 Gas disk migration

The runaway, oligarchic, and early post-oligarchic stages of planet formation are accompanied by the continuing presence of residual gas within the protoplanetary disk. Gravitational interaction between protoplanets and the disk plays a prominent role in shaping planetary systems in the early stages of their formation and evolution.

A planet moving through the gas disk excites spiral density waves within it, and the torque exerted by the perturbed disk drives gap opening and orbital migration, viz. a change in the planet's semi-major axis, throughout the lifetime of the disk.

Both the speed of migration, as well as its direction (inward or outward) depend on the planet mass, and the disk properties near the planet's orbital radius, including the turbulent viscosity (§10.3.2), density and temperature profiles, and magnetic fields (e.g. Goldreich & Tremaine, 1979, 1980; Lin & Papaloizou, 1993; Lin et al., 2000; Nelson et al., 2000; Terquem et al., 2000; Papaloizou & Nelson, 2003; Nelson & Papaloizou, 2003, 2004; Papaloizou & Terquem, 2006; Yu et al., 2010).

In all cases, gas disk migration must take place while the primordial disk of gas and dust is still present, viz. during the first 3–5 Myr of the host star's life (§10.3.6).

In practice, several regimes of migration are distinguished, based on the planet's influence in opening an annular gap around its orbit, which itself depends on the planet to primary mass ratio, the disk's aspect ratio,  $h$ , and the viscosity parameter characterising the effect of turbulence,  $\alpha$  (§10.3.2). For typical disks in regions of planet formation ( $h \sim 0.05$ ,  $\alpha$  a few  $\times 10^{-3}$ ), type I migration applies to planets up to  $10 - 20 M_{\oplus}$ . Giant planets in the Jupiter-mass range carve a deep gap around their orbit and experience type II migration. Subgiant planets that open a partial gap may undergo type III runaway migration in more massive disks.

**Corotation and Lindblad resonances** Excited density waves are particularly pronounced at the locations of the corotation and Lindblad resonances (Binney & Tremaine, 2008), and the planet experiences a torque exerted by each of them. For a planet on a circular orbit with angular frequency  $\Omega_p$ , the *corotation resonance* exists at the radius in the disk where

$$\Omega = \Omega_p . \quad (10.53)$$

Multiple inner and outer *Lindblad resonances* occur for

$$m(\Omega - \Omega_p) = \pm \kappa_0 , \quad (10.54)$$

where  $m$  is an integer, and  $\kappa_0$  is the epicyclic frequency. For a Keplerian disk,  $\kappa_0 = \Omega$ , and their radii are at

$$r_L = r_p \left( 1 \pm \frac{1}{m} \right)^{2/3} , \quad (10.55)$$

where  $r_p$  is the orbital radius of the planet.

Goldreich & Tremaine (1979, 1980) derived expressions for the torques on the planet embedded in a two-dimensional disk. The net torque, mainly resulting from the positive torques exerted by the Lindblad resonances located interior to the planet and the negative torques exerted by the exterior Lindblad resonances, causes the radial orbit migration of the planet. For the more general case of eccentric orbits, (non-coorbital) corotation resonances still exist, but now at harmonics of the mean motion angular frequency (Artymowicz & Lubow, 1994; Papaloizou & Larwood, 2000; Fendyke & Nelson, 2014).

**Type I migration** Evolution of the planet's orbit under the condition that the gas surface density profile remains approximately unperturbed is referred to as *type I migration* (Figure 10.35a).

If turbulence determines the density structure of the disk, the disk response can be described using linear analysis (Ward, 1997a; Murray et al., 1998; Cresswell et al., 2007). Analytical and numerical simulations show that this condition holds for  $M_p \lesssim 10\text{--}20M_\oplus$ . The migration time varies inversely with  $M_p$ , and type I migration is consequently most rapid for the largest body for which the assumptions that the gas disk remains unaffected by the planet remains valid.

As the gas disperses, type I migration slows, possibly to the point that the planet survives for the remaining life of the disk. Accretion may then be inefficient (McNeil et al., 2005), and planet formation may be most successful in low-mass disks where migration is less rapid.

The torque acting on type I migrating planets has two main components (Baruteau & Masset, 2013; Guilet et al., 2013): the differential Lindblad torque, and the corotation torque, and the overall torque on the planet is found by summing the individual torques exerted by each resonance (Figure 10.34).

The differential *Lindblad torque* results from angular momentum carried away by the spiral density waves (wakes) generated by the planet. Its sign and amplitude (dependent mainly on the local temperature gradient) result from a slight asymmetry in their density distribution (Ward, 1997a). For typical density and temperature profiles, the differential Lindblad torque is negative: in the absence of other forces, the planet would migrate inwards, on a time scale much shorter than the lifetime of protoplanetary disks (e.g. Tanaka et al., 2002).

As an example, for a low-mass protoplanetary disk with  $\Sigma(r) = 1500(r/5\text{ au})^{-3/2} \text{ kg m}^{-2}$  at  $T = 130 \text{ K}$ , the net differential Lindblad torque in both 2d (e.g. Hourigan & Ward, 1984; Ward, 1986; Korycansky & Pollack, 1993) and 3d disks (e.g. Lubow & Ogilvie, 1998; Takeuchi & Miyama, 1998; Miyoshi et al., 1999; Tanaka et al., 2002; Terquem & Papaloizou, 2007) would result in an inward migration time for an Earth-sized planet at 5 au of  $\tau_1 \sim 0.1\text{--}1 \text{ Myr}$ . This is significantly shorter than the time required for the formation of giant planets by core accre-

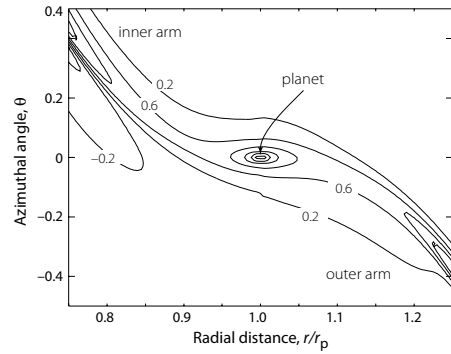


Figure 10.34: Surface density perturbations excited by a planet in a 3d disk, in the  $(r, \theta)$  plane. High surface density arms are formed inside and outside the planet orbit, the inner exerting a positive torque on the planet, and vice versa. Their asymmetry causes the net Lindblad torque on the planet, contributing to type I migration. Similar forms are found from hydrodynamical simulations (e.g. Miyoshi et al., 1999). From Tanaka et al. (2002, Figure 6a), by permission of IOP Publishing/AAS.

tion, of order  $10^7 \text{ yr}$  (§10.5.1).

The *corotation torque* (or *horseshoe drag*) accounts for the angular momentum exchanged between the planet and the disk material within its co-orbital region. Including the effects of both corotation and Lindblad resonances, Tanaka et al. (2002) found that, for a 3d isothermal gas disk with surface profile  $\Sigma(r) \propto r^{-\gamma}$ , the migration time scale is given by (their equation 70)

$$\tau_1 = \frac{1}{(2.1 + 1.1\gamma)} \frac{M_\star}{M_p} \frac{M_\star}{r_p^2 \Sigma(r_p)} \left( \frac{c_s}{r_p \Omega_p} \right)^2 \frac{1}{\Omega_p}, \quad (10.56)$$

where  $\Sigma(r_p)$ ,  $c_s$ , and  $\Omega_p$  are respectively the gas surface density, sound speed, and angular velocity at the location of a planet orbiting at distance  $r_p$ . As in the 2d case, the migration speed is proportional to the planet mass and the disk surface density, although longer than in the two-dimensional case by a factor 2–3.

Radiation transport in a non-isothermal disk further modifies the corotation torque, with an amplitude comparable to, or exceeding that of the differential Lindblad torque, and resulting in a slower or even reversed (outward) migration (Paardekooper & Mellema, 2006).

Population synthesis models (§10.13) have shown that type I migration needs to be significantly reduced over a wide region of the disk for a long time. However, a mechanism capable of suppressing it, over a wide parameter space, has remained elusive.

**Detailed models** These and other effects modifying type I migration have been modeled in detail, including different surface density and temperature profiles, different viscosity and adiabatic index, different orbit eccentricities, and effects such as turbulence-driven disk winds (Laughlin et al., 2004b; Jang-Condell & Sasselov, 2005; Johnson et al., 2006a; Masset et al., 2006; Paardekooper & Mellema, 2006; Baruteau & Masset, 2008; Kley & Crida, 2008; Paardekooper & Papaloizou, 2008;

Adams & Bloch, 2009; Adams et al., 2009; Casoli & Masset, 2009; Kley et al., 2009; Crida et al., 2009a; Masset & Casoli, 2009; Paardekooper & Papaloizou, 2009; Ayliffe & Bate, 2010; Bitsch & Kley, 2010; Lyra et al., 2010; Masset & Casoli, 2010; Paardekooper et al., 2010a; Ayliffe & Bate, 2011; Bitsch & Kley, 2011b; Bromley & Kenyon, 2011a; Masset, 2011; Paardekooper et al., 2011a; Tsang, 2011; Yamada & Inaba, 2011, 2012; Bitsch et al., 2013a; Dunhill et al., 2013; Fendyke & Nelson, 2014; Lega et al., 2014; Duffell, 2015; Ogihara et al., 2015c; Pierens & Raymond, 2016; Jiménez & Masset, 2017).

In viscous disks, the corotation torque is the sum of: (i) a term proportional to the vortensity gradient (see §10.3.5) across the horseshoe region (the *vortensity-related corotation torque*), which arises from the advection–diffusion of vortensity (Masset, 2001, 2011; Paardekooper, 2014); (ii) a term proportional to the entropy gradient across the horseshoe region (the *entropy-related corotation torque*), originating from the production of vortensity at the downstream separatrices of the horseshoe region (Masset & Casoli, 2009; Paardekooper et al., 2010a).

The sign and amplitude of the total corotation torque depend on the disk’s density and temperature profiles across the planet’s horseshoe region, as well as on its viscosity and thermal diffusivity. Its potentially large amplitude means that it can play an important role in the evolution of young planetary systems, and various analytic formulae for its effect have been constructed (Masset & Casoli, 2010; Paardekooper et al., 2011a).

For type I migrating planets, the width of the horseshoe region is a fraction of the disk’s pressure scale height, and thus of the typical size of turbulent eddies. The behaviour of the corotation torque in turbulent disks (as opposed to viscous disks) has been variously studied (e.g. Baruteau & Lin, 2010; Baruteau et al., 2011a; Uribe et al., 2011; Pierens et al., 2012). Adopting the turbulence model of Laughlin et al. (2004b), where turbulence is generated by stochastic forcing, 2d hydrodynamical simulations show that both the differential Lindblad torque and the corotation torque behave as in equivalent laminar viscous disks (Baruteau & Lin, 2010; Pierens et al., 2012).

Magnetic fields further modify migration (e.g. Terquem, 2003; Fromang et al., 2005; Baruteau et al., 2011a). The interaction between the magnetic field and the horseshoe motion of the gas results in an additional torque, the *magnetohydrodynamic torque excess* (Guilet et al., 2013). Its sign (and radial form) depends on the density and temperature gradients, and is positive for typical protoplanetary disk profiles. Its magnitude is mainly determined by the magnetic field strength and the turbulent resistivity. It can be strong enough to reverse migration even when the magnetic pressure is less than 1% of the thermal pressure, and can therefore lead to outward planetary migration in the radiatively efficient outer disk regions where the hydrodynamical corotation torque is too weak to prevent fast inward migration (Guilet et al., 2013).

An additional torque causing low-mass planets to migrate outwards can be generated by density waves excited by a gas giant on an interior orbit (Podlowska-Gaca et al., 2012).

Type I migration can be locally outward depending on disk properties (Kretke & Lin, 2012; Bitsch et al., 2015). Region of local outward migration can arise from inhomogeneities in disks (e.g., opacity transitions), and such local inhomogeneities may help in reducing the type I migration speed (Dittkrist et al., 2014; Mordasini et al., 2015).

**Convergence zone** With the finding that net type I migration can be either inward or outward depending on local disk properties, a protoplanet moving outwards in a non-isothermal disk will cease migration at some equilibrium (or zero torque) ra-

dius, estimated at  $1.4 - 2.4a_j$  for  $30 - 20M_{\oplus}$  cores respectively (Bitsch & Kley, 2011b). A body migrating inwards from farther out will stop at a similar location, creating a *convergence zone* (or ‘feeding zone’), and facilitating further mergers (e.g. Lyra et al., 2010; Bitsch & Kley, 2011b).

Mutual interactions do not necessarily eject objects from the convergence zone: in a laminar disk, small numbers can settle into near-resonant orbits that remain stable over 10 Myr (Horn et al., 2012). Increasing the numbers of embryos, or including a correlated stochastic force to represent turbulence, may drive orbit crossings and mergers, leading to the creation of gas giant cores of  $10M_{\oplus}$  from sub- $M_{\oplus}$  embryos in 2–3 Myr. Cossou et al. (2013) found yet more complex behaviour from N-body simulations: systems of low-mass ( $1 - 10M_{\oplus}$ ) planets can become trapped in chains of mean motion resonances, affecting the structure of the horseshoe region, moving the effective convergence zone inward, and generating stochastic migration due to continuous perturbations from planets entering and leaving resonances.

**Disk winds** Turbulence-driven disk winds, in which gas is blown away from the disk’s surface (§10.3.4), can also alter the density profile of the gas disk (Suzuki & Inutsuka, 2009; Suzuki et al., 2010). This can slow down or reverse type I migration, over a wide range of disks (Ogihara et al., 2015a,c).

Ogihara et al. (2015a) also demonstrated that disk winds can reproduce characteristic features (notably mass concentrations) of the solar system terrestrial planets. They have also been considered in the context of *in situ* formation of close-in super-Earths (Ogihara et al., 2015b,c).

**Planets formed by gravitational instability** With the assumption of a  $1M_J$  planet formed at 25 au by gravitational instability, resulting behaviour is complex, with slow migration punctuated by intervals of more rapid inward or outward motion (Michael et al., 2011). Simulations by Baruteau et al. (2011b) suggest that a similar planet placed at 100 au migrates rapidly inwards through the gravitoturbulent disk, despite stochastic kicks. With no time to open a gap, the time scale is comparable to that of type I migration, with inward migration in as little as  $10^4$  yr, or some 10 orbits at 100 au. Similar results are demonstrated by Zhu et al. (2012a).

**Type II migration** Type I migration is characterised by an azimuthally-averaged gas surface density profile which is largely unperturbed by the planet. For larger planet masses, the surface density profile of the disk is modified by the presence of the planet. The planet’s tidal torques dominate the viscous torques of the disk, gas is repelled from the vicinity of the planet, and an annular gap in the gas opens up at the orbital radius of the planet (Figure 10.35b).

The resulting orbital evolution, in which angular momentum exchange occurs through a combination of wave excitation and shock dissipation, is referred to as *type II migration*. Type II migration provides a mechanism to transport gas giants that must form beyond the snow line inward to their host star, with migration occurring at the viscous speed of the disk. Inward migration augments the material which can be captured in a giant planet’s envelope, effects which are considered more specifically in Section 10.5.1.

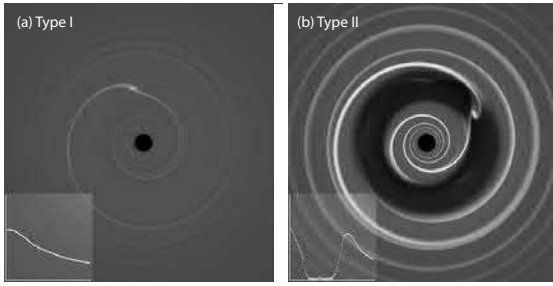


Figure 10.35: Type I and type II migration. Simulations of the interaction between a planet on a circular orbit with a laminar (non-turbulent) protoplanetary disk, computed from a 2D isothermal hydrodynamic code with a constant kinematic viscosity: (a) in type I migration, a relatively low-mass planet excites a wave in the gas disk, but does not significantly perturb the azimuthally-averaged surface density profile (inset); (b) in type II migration, a more massive planet (here  $10M_J$ ) clears an annular gap, within which the surface density is a small fraction of its unperturbed value. As the disk evolves, the planet follows the motion of the gas (either inward or outward) while remaining within the gap. From Armitage & Rice (2005, Figure 1).

Two conditions are necessary for gap formation (Armitage, 2007a, eqn 212–216). The first is that the radius of the planet’s Hill sphere (box, page 512) is larger than the thickness of the gas disk. This corresponds to

$$R_H \equiv \left( \frac{M_p}{3M_\star} \right)^{1/3} r \gtrsim h, \quad (10.57)$$

which requires

$$\frac{M_p}{M_\star} \gtrsim 3 \left( \frac{h}{r} \right)^3. \quad (10.58)$$

For typical protoplanetary disks with aspect ratio  $h/r \sim 0.05$ , this is satisfied for  $M_p/M_\star \sim 10^{-4}$ , i.e. for planets between the mass of Saturn and Jupiter.

The second condition is that maintaining a gap requires that tidal torques must remove gas from the gap faster than viscosity will allow it to be replenished (Goldreich & Tremaine, 1980; Lin & Papaloizou, 1980; Papaloizou & Lin, 1984; Lin & Papaloizou, 1986a,b; Ward & Hourigan, 1989; Takeuchi et al., 1996). Armitage (2007a, eqn 216) gives for this condition

$$\frac{M_p}{M_\star} \gtrsim \left( \frac{c_s}{r_p \Omega_p} \right)^2 \alpha^{1/2}. \quad (10.59)$$

For  $\alpha$ -disks with  $\alpha \sim 0.01$ , this implies  $M_p/M_\star \gtrsim 10^{-4}$ .

For the two conditions taken together, Jupiter-mass planets should be massive enough to force gap opening, while Saturn-mass planets may be only marginally so. A more massive planet is required to open a comparable gap when the planet is on an eccentric orbit (Hosseini et al., 2007).

Once a gap is opened, orbital evolution is expected to occur on the same time scale as the viscous time scale

of the protoplanetary disk (Shakura & Sunyaev, 1973; Ward, 1997a), giving a type II migration time scale (Papaloizou & Terquem, 2006, eqn 75)

$$\tau_{II} = \frac{1}{3\alpha} \left( \frac{r_p}{h} \right)^2 \frac{1}{\Omega_p}. \quad (10.60)$$

For an  $\alpha$ -disk with  $\alpha = 0.01$  and  $h/r = 0.1$ , this gives  $\tau_{II} \sim 10^3 - 10^4$  yr at  $r_p = 1 - 5$  au, very much shorter than the disk lifetime or planetary formation time scale.

More detailed models include modifications in the disk surface density (Syer & Clarke, 1995); the finite disk accretion rate (Bell et al., 1997); tidal streams that bridge the gap for marginal gap-opening masses (Lubow et al., 1999; Lubow & D’Angelo, 2006; Duffell et al., 2014); magnetic activity and gas disk dispersal (Armitage, 2002); global disk evolution (Crida & Morbidelli, 2007); the minimum planet mass for gap opening (Edgar et al., 2007); spiral groove modes (Meschiari & Laughlin, 2008); gravitational instabilities associated with the disk or gap (Lin & Papaloizou, 2012; Boss, 2013b; Cloutier & Lin, 2013; Zhang et al., 2014a); dead zones and photo-evaporation (Hasegawa & Ida, 2013), the transition from type I to type II regimes (Crida & Bitsch, 2017), and resonance capture (Antoniadou & Voyatzis, 2017).

Population synthesis models (§10.13) showed that standard type II migration is too rapid to match the observations. In practice, instead of a perfect gap formed by the planet, gas crosses the gap or is accreted by the planet. The resulting migration rate, determined by the disk torques, can then be faster or slower than type II migration (Dürmann & Kley, 2015, 2017).

There is no general consensus on the relative importance of the various mechanisms which might slow, inhibit, or reverse the resulting inward migration. However, tidal circularisation will occur if the planet arrives within a few  $R_\star$ , i.e., within a few 0.1 au (§10.11).

**Observational confirmation** Observational confirmation of the existence of such forming planets, and the annular gaps directly associated with them, has been assessed for ALMA (§3.11.2) at sub-mm wavelengths (Wolf et al., 2002; Wolf & D’Angelo, 2005; Brogan et al., 2015).

At optical wavelengths, relevant observations are starting to appear with the second-generation imaging instruments Gemini-GPI, VLT-SPHERE, Subaru-HiCIAO, and LBT (§7.6.2). Gaps possibly attributable to planets (as opposed to gaps in transition disks, §10.3.8) have been imaged, for example, in HD 97048 (Ginski et al., 2016b); HD 169142 (Momose et al., 2015); LkCa 15 (Sallum et al., 2015); RX J1615.3–3255 (de Boer et al., 2016); and TW Hya (Akiyama et al., 2015).

Scale heights of the disks, and possible masses of the candidate gap-opening planets, can be derived assuming each gap is opened by a single planet. For  $\alpha = 10^{-3}$ , the derived planet masses fall roughly between 0.1 –  $1M_J$  (Dong & Fung, 2017b).

**Type III migration** For a smooth initial density profile in the disk, and a small density gradient at the corotation radius, the corotation torques are less pronounced

than those arising from the Lindblad resonances. Under certain circumstances, however, the corotation resonance can modify the type I migration rate substantially (Masset & Papaloizou, 2003; Artymowicz, 2004a,b; Masset et al., 2006; Paardekooper & Mellema, 2006), possibly leading to particularly rapid migration referred to as *type III migration*, or *runaway migration*.

The effect depends strongly on the mass accumulation rate, and on the structure of the gas flow in the coorbital region and, like type I migration in principle, does not have a predetermined direction. Two- and three-dimensional simulations have been carried out, covering both inward and outward migration (Masset & Papaloizou, 2003; D'Angelo et al., 2005; Papaloizou, 2005; Pepliński et al., 2008a,b,c; Cloutier & Lin, 2013; Malik et al., 2015).

Simulations show a transition from the fast to a slow regime, which ends type III migration well before the planet reaches the star. In the fast regime the migration rate and induced eccentricity are lower for less massive disks, but are reasonably independent of planet mass. Eccentricity is damped on the migration time scale.

**Halting migration** While type II migration within the residual gas disk provides a mechanism to transport gas giants from beyond the snow line inward to their host star, early theoretical models of both type I and type II migration suggested that rapid inward migration would typically result in the planet's tidal destruction (e.g. Ward, 1997b,a). Amongst a variety of suggested braking, trapping, and halting mechanisms, there is no complete picture of how planet migration is halted and tidal disruption averted. At least part of this uncertainty is because close-in planets appear to arise from various processes, planet–planet scattering and Lidov–Kozai oscillation as well as inward migration, and the halting conditions and requirements differ for each.

Perhaps the simplest conceptual picture is that migration would cease at any radius when the disk dissipates (Trilling et al., 1998, 2002; Lecar & Sasselov, 2003), although this requires fine tuning of the disk mass and lifetime to explain the observed population. Similarly, a giant planet could survive if, after formation, not enough disk material was for significant migration to occur. In this scenario, a number of giant planets could assemble and fall onto the star (Gonzalez, 1997; Laughlin & Adams, 1997), with disk material left over to allow a further planet to form but not migrate (Lin, 1997).

The halting of inwardly migrating planets is generally attributed to some sort of inner truncation of the protoplanetary disk, for example due to the host star magnetosphere (e.g. Lin et al., 1996; Shu et al., 2000; Eisner et al., 2005; Romanova & Lovelace, 2006; Rice et al., 2008; Adams et al., 2009; Hasegawa & Pudritz, 2011a; Lee & Chiang, 2017).

**Other halting mechanisms** Other mechanisms which might contribute to braking, trapping, or halting include: trapping the planet in the 1:2 interior orbital resonance with the dust sublimation radius (Kuchner & Lecar, 2002; Baillié et al., 2016); disk turbulence (Lubow & Ida, 2010; Menou & Goodman, 2004); Roche lobe overflow (Trilling et al., 1998; Hansen & Barman, 2007), possibly as a result of inflation due to Ohmic heating caused by the planet's response to the star's tilted magnetic field (Laine et al., 2008); stellar magnetospheric winds (Lovelace et al., 2008; Strugarek, 2016; Strugarek et al., 2017); photoevaporation of the disk (Matsuyama et al., 2003; Hasegawa & Pudritz, 2012); holes in the protoplanetary disk arising from magnetorotational instabilities (Kuchner & Lecar, 2002; Matsumura & Pudritz, 2005; Papaloizou et al., 2007); magnetic resonance torques in the disk (Terquem, 2003); magnetorotational turbulence (Laughlin et al., 2004b; Nelson & Papaloizou, 2004; Comins et al., 2016); perturbations from a nearby star (Mal'Nev et al., 2006); twisted magnetic toroidal–poloidal torques linking the star and planet (Fleck, 2008); eccentricity trapping (Ogihara et al., 2010; Muto et al., 2011); and resonant trapping (considered below), leading to a reversal of type II migration.

A slightly different picture would follow if the close-in planets reached their present configurations through tidal circularisation following planet–planet scattering (§10.10.4) or Lidov–Kozai oscillation (§10.10.6), rather than migration. For planets delivered in this way to very close-in orbits, tidal decay may continue, eventually to destruction, even after circularisation. Hot and very hot Jupiters might then simply be those next in line for tidal destruction, after the many that have already spiraled into their host stars (Jackson et al., 2009). The short infall time inferred for some of the shortest-period planets (§6.14.21), such as HAT-P-23 and Kepler-91, would be a consequence.

Indirect evidence for this mechanism may come from the chemical pollution (§8.4.3) or spin-up (§10.11) of host stars which have consumed a close-in planet. Even in these cases, tidal destruction could be halted, or at least delayed, if spin-up of the host star leads to tidal locking in which the rotation period of the host star becomes equal to that of the orbital period as the planet spirals inward.

For a population still dominated by inward migration, the inner edge of the mass–period distribution should correspond to the Roche radius. For a population resulting from initially eccentric orbits subsequently tidally circularised, the inner edge should correspond to twice the Roche radius (Pätzold & Rauer, 2002; Ford & Rasio, 2006).

**Observational constraints on halting** Many observations have been used to provide constraints on halting mechanisms. Plavchan & Bilinski (2013) used the observed distribution of confirmed planets and Kepler candidates in the ( $M_*$ ,  $a_p$ ) plane as a diagnostic for various possible migration-halting mechanisms. For tidal circularisation, they used two predictions for the stopping radius: a scaling from the Roche radius, with  $a \propto M_*^{1/3}$  (Ford & Rasio, 2006), or slightly steeper (Guillochon et al., 2011); and one (derived from assumed Kozai circularisation) with a slightly different dependence on stellar mass,  $a \propto M_*^{3/13}$ , and weakly dependent on the unknown planet resonant  $Q$  factor (Wu et al., 2007, eqn 6). They found that halting by tidal circularisation provides the best fit to all their samples, although favouring a dependence of halting radius with stellar mass that is stronger than predicted from tidal dissipation theories. For the majority of observed close-in exoplanets, they excluded halting at the 1:2 interior resonance with the magnetospheric disk truncation radius, at the 1:2 interior resonance

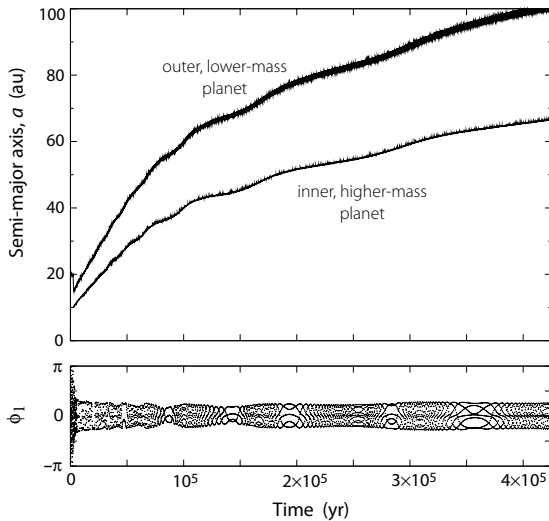


Figure 10.36: Resonant migration for two planets initially at  $a = 10$  and  $20$  au, orbiting a  $M_{\star} = 2M_{\odot}$  star, within a disk of surface density  $\Sigma = 2666 \text{ kg m}^{-2}$  at  $10$  au. Top: semi-major axes as a function of time. Bottom: resonant angle  $\phi_1 = 2\lambda_2 - \lambda_1 - \bar{\omega}_1$  (Equation 10.33) as a function of time. From Crida et al. (2009b, Figure 1), by permission of IOP Publishing/AAS.

with the dust sublimation radius, and any uniform halting radius independent of  $M_{\star}$ .

In contrast, Lee & Chiang (2017) appealed to the distribution of sub-Neptunes around FGKM dwarfs, finding them evenly distributed in log period down to  $\sim 10$  d, but smaller in number at shorter periods. Both the break at  $\sim 10$  d, and the slope down to  $\sim 1$  d, could be attributed to disk truncation by their host star magnetospheres at corotation.

**Resonant trapping and migration** The discovery, through imaging, of exoplanets orbiting at distances out to  $a \sim 120$  au, notably those surrounding Fomalhaut and HR 8799 (§7.10.2), provides another challenge to formation theories: at these distances, typical dynamical and accretion time scales are expected to be too long to allow their formation *in situ*. Various possibilities have been considered to explain their existence.

In the first, planet formation by gravitational instability remains effective in the outer parts of the disk beyond  $\sim 50$ – $100$  au, in regions where the cooling time relative to the dynamical time becomes short, and where the Toomre  $Q$  parameter may be smaller (§10.5.2).

Alternatively, they may have formed at  $5$ – $20$  au, and their current large semi-major axes may have resulted from scattering with other giant planets (§10.10.4), perhaps producing a population of giant planets as distant as  $\sim 100$ – $10^5$  au (Veras et al., 2009).

A third possibility, *resonant trapping*, combines type II migration with the mechanism by which two migrating planets can become trapped in mean motion resonance (see §10.8.2). Under certain conditions during type II migration, resonant trapping can reverse the

normal inward migration, resulting in an outward migration of both planets (Masset & Snellgrove, 2001; Snellgrove et al., 2001; Yu & Tremaine, 2001; Murray et al., 2002; Papaloizou, 2003; Ferraz-Mello et al., 2003; Wyatt, 2003; Kley et al., 2004; Veras & Armitage, 2004b; Kley & Sándor, 2007; Martin et al., 2007; Pierens & Nelson, 2008a; Crida et al., 2008; Pierens et al., 2011; Michtchenko & Rodríguez, 2011; Rodríguez et al., 2011b; Szuszkiewicz & Podlowska-Gaca, 2012; Xiang-Gruess & Papaloizou, 2015).

Specifically, if two planets open up overlapping gaps, then the inner planet experiences a positive torque from the inner disk, but a reduced torque from the disk's outer parts. Similarly, the outer planet experiences a mostly negative torque from the outer disk. If the inner planet is more massive, the total torque applied to the pair is positive, and a resonantly trapped pair then migrate outwards together.

The importance of the effect depends on a number of factors. To continue over a long period, material lying outside of the common gap must be funneled towards the inner disk, and the inner disk must also be replenished (Crida et al., 2009b). The drift rate is also a decreasing function of the disk's aspect ratio, with the one-sided Lindblad torque being proportional to  $(h/r)^{-3}$  (Masset & Snellgrove, 2001; Morbidelli & Crida, 2007).

Simulation results from Crida et al. (2009b) are shown in Figure 10.36. This models the evolution of the semi-major axes for a pair of outwardly migrating planets, initially at  $r = 10$  and  $20$  au, for a disk surface density  $\Sigma = 2666 \text{ kg m}^{-2}$  at  $10$  au (6.6 times heavier than the minimum-mass solar nebula, §10.3), and with  $M_{\star} = 2M_{\odot}$ , corresponding to the case of Fomalhaut. The outer planet migrates to  $100$  au in  $4 \times 10^5$  yr, reaching the same distance in  $4 \times 10^6$  yr in a disk a factor of ten less massive.

The model of Crida et al. (2009b) predicts that, in the Fomalhaut system with Fomalhaut b at  $115$  au (Kalas et al., 2008), a second planet, with  $M_p \sim 1$ – $10M_J$ , should now be orbiting at  $\sim 75$  au.

**Modification of eccentricities** The same disk torques which cause migration also alter the orbital eccentricities and inclinations of the migrating planet. Whether eccentricities undergo growth or decay depends on the relative strengths of the Lindblad resonances which increase eccentricity, and (non-coorbital) corotation resonances which act to damp it (Goldreich & Tremaine, 1980; Artymowicz, 1993; Goldreich & Sari, 2003; Moorhead & Adams, 2008).

Some analytic estimates suggest that, for low-mass planets,  $e$  and  $i$  can be damped on time scales  $10^2$ – $10^3$  times shorter than the migration time (e.g. Tanaka & Ward, 2004), and this damping may play a significant role in orbit circularisation for terrestrial planets (Komami & Ida, 2002), at least for the  $10$  Myr until disk dispersal (Pascucci et al., 2006).

If the planet is of sufficient mass to clear a gap in the disk, the efficiency of eccentricity damping by coorbital Lindblad resonances is reduced, and eccentricity excitation may dominate (Goldreich & Sari, 2003; Ogilvie & Lubow, 2003; Sari & Goldreich, 2004; Masset & Ogilvie, 2004). While such eccentricity growth is not predicted for Jovian mass planets, the effect becomes important for brown dwarf masses and above (Artymowicz et al., 1991; Papaloizou et al., 2001).

It has been suggested that a subset of low-obliquity hot Jupiters could originate from migration combined with secular gravitational interactions between two planets in eccentric orbits with relatively low mutual inclinations, with orbits subsequently tidally circularised. Termed ‘co-planar high-eccentricity migration’, this allows for migration to occur in the same plane in which the planets formed (Petrovich, 2015a; Xue et al., 2017).

**Excitation of inclinations** Resonance trapping in type II migration may lead to systems in which the planetary orbit planes have a significant value of mutual inclination. For planets in a 2:1 mean motion resonance within the protoplanetary gas disk, and with sufficiently high eccentricities, Thommes & Lissauer (2003) found that the system can enter an ‘inclination-type’ resonance, inducing rapid growth in their inclinations.

Libert & Tsiganis (2009b) showed that capture into higher order resonances (such as the 5:2, 3:1, 4:1 and 5:1) are possible for a wide range of migration and eccentricity damping rates ( $\dot{a}$  and  $\dot{e}$ ), and that these can also excite inclinations to high values, provided that eccentricity damping is not very strong. Libert & Tsiganis (2011a) simulated triple resonance configurations, showing that one of the three planets is typically ejected from the system, leaving behind a dynamically ‘hot’ (but stable) two-planet configuration. The resulting two-planet systems typically have large values of semi-major axis ratios ( $a_1/a_2 < 0.3$ ), while the mutual inclination can be as high as  $70^\circ$ , with a median of  $\sim 30^\circ$ . Voyatzis et al. (2014) showed that from a modestly non-coplanar starting configuration, resonant capture can still occur, and can lead to the excitation of planetary inclinations.

The conclusion of these studies is that high inclinations can be quite common in resonant systems, possibly as exemplified by  $\nu$  And (§3.7). Such ‘3d’ systems can be long-term stable, either following regular secular dynamics or due to the action of some phase-protection mechanism, such as a mean motion resonance or a secular Kozai-type resonance, with some 5% of their 2-planet systems ending up in the stability zone of Kozai resonance (§10.10.6). In the associated single-planet systems, formed when two of the planets are ejected, the inclination of the planet’s orbital plane with respect to the initial invariant plane can be as large as  $40^\circ$ .

Damping formulae for  $i$  and  $e$  as a function of  $i$ ,  $e$ , and  $M_p$  are derived by Bitsch et al. (2013b).

**Migration and the brown dwarf desert** Armitage & Bonnell (2002) proposed that the dearth of brown dwarfs in short-period orbits around solar mass stars, the ‘brown dwarf desert’ (§2.10.5), is a consequence of inward migration in the presence of an evolving protoplanetary disk. Brown dwarf secondaries forming at the same time as the primary star have masses which are comparable to the initial mass of the protoplanetary disk, and are destroyed via merger with the star as a result of inward migration (Matzner & Levin, 2005). Massive planets forming at a later epoch, when the disk is largely dispersed, survive.

**Continued existence of terrestrial planets** Dynamical simulations by Mandell & Sigurdsson (2003) suggest that a significant fraction of existing terrestrial planets could survive the inward migration of a giant planet, possibly returning to near circular orbits relatively close to their original positions. Although the migrating giant moves through various orbital resonances with the inner planets, and may excite large eccentricities, the dynamics are chaotic, and the fate of specific planets is highly dependent on initial conditions (e.g. Matsumura et al., 2013). Once the giant planet has moved sufficiently close to the star, it is effectively decoupled from any remaining bound terrestrial planets, which then settle into quasi-stable orbits. A fraction of the final orbits are in the habitable zone, suggesting that planetary systems with close-in giant planets remain viable targets for searches for Earth-like habitable planets (Jones et al., 2006a). A population of planetesimals of very high eccentricity and inclination may persist as signatures of such events (Lufkin et al., 2006; Veras & Armitage, 2006).

If a giant planet forms and migrates quickly, the planetesimal population may have time to regenerate within the lifetime of the disk, and terrestrial planets may still be able to form thereafter, albeit with a reduced efficiency (Armitage, 2003). Potentially habitable planets may only be able to form for small final orbital radii of the hot Jupiter,  $a \lesssim 0.25$  au, while for  $a \gtrsim 0.5$  au their formation appears to be suppressed (Raymond et al., 2005a; Raymond, 2006). Nevertheless, water-rich terrestrial planets should be able to form in the habitable zones of hot Jupiter systems, along with hot Earths and hot Neptunes, even for modest giant planet orbital eccentricities (Fogg & Nelson, 2005; Mandell et al., 2007; Fogg & Nelson, 2007a,b, 2009).

A system which may provide evidence for such a migration scenario is WASP-47. Discovered as a ( $P = 4.2$  d,  $M = 1.2M_J$ ) hot Jupiter (Hellier et al., 2012), it was later found to be accompanied by both inner and outer transiting  $10 - 12M_\oplus$  planets (Becker et al., 2015), along with a second more distant Jupiter-mass companion ( $P = 580$  d,  $M = 1.6M_J$ ) discovered from radial velocity measures (Neveu-VanMalle et al., 2016).

Similar architecture may be exhibited by Kepler-30, in which the three planets include a  $P = 60$  d,  $M = 2M_J$  planet orbiting between the inner ( $P = 29$  d,  $M = 11M_\oplus$ ) and outer ( $P = 143$  d,  $M = 23M_\oplus$ ) planets (Sanchis-Ojeda et al., 2012).

### 10.10.3 Planetesimal disk migration

After formation of the terrestrial and gas/ice giants, and after dispersal of the gas disk, planet migration may still occur as a result of gravitational scattering between the planets and any remaining planetesimals (Baruteau et al., 2014).

For a planetesimal of mass  $\delta m$  interacting with a planet of mass  $M_p$  at orbital radius  $r$  then, by conservation of angular momentum, an inward scattering of the

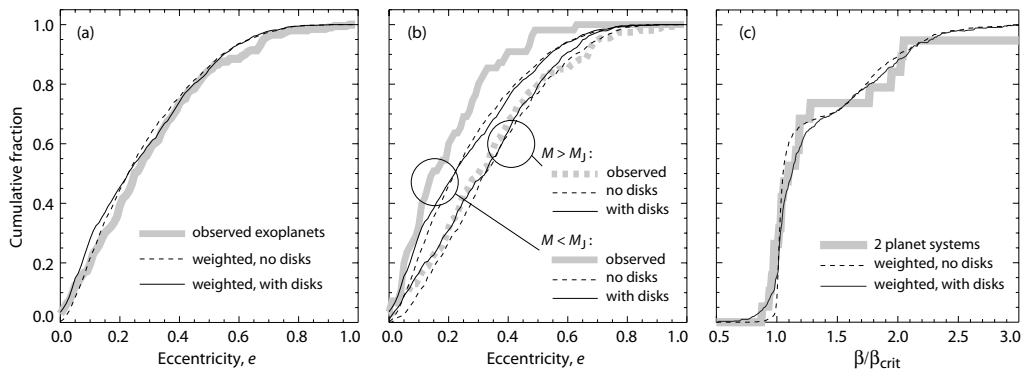


Figure 10.37: Simulations versus observed distributions for numerical experiments based on both planet–planet and planetesimal disk scattering, showing: (a) the cumulative eccentricity distribution, (b) the eccentricity distribution subdivided by mass, and (c) the measure of the proximity of a pair of orbits to the Hill stability limit,  $\beta/\beta_{\text{crit}}$ . Observed distributions are shown by the thick lines, while the simulations, with and without planetesimal disks, are shown by solid and dashed lines, respectively. From Raymond et al. (2010, Figures 1 and 21), by permission of IOP Publishing/AAS.

planetesimal will be accompanied by an outward movement of the planet, and *vice versa*, leading to a planet displacement of order (Malhotra, 1995; Armitage, 2007a)

$$\frac{\delta r}{r} \sim \pm \frac{\delta m}{M_p} \quad (10.61)$$

respectively. For significant migration, the total mass of scatterable planetesimals should be at least comparable to that of the planet. Any given planet may be expected to undergo only limited overall migration as a result of comparable numbers of inward and outward scatterings; to first order, the torques exerted by the interior and exterior disks will cancel, analogous to the case of Type I migration due to the gas (§10.10.2).

Detailed studies show considerable dependence on the (assumed) planetesimal surface density distribution, and the assumed distributions of their masses, eccentricities, and inclinations. For example, the N-body simulations of Kirsh et al. (2009), using  $10^4 - 10^5$  equal-mass planetesimals, resulted in rapid planet migration at a rate independent of  $M_p$ , provided that  $M_p$  was not large compared to the mass in planetesimals capable of entering its Hill sphere). Both inward and outward migrations can be self-sustaining, with a strong tendency for inward migration. When a gas disk is also present, aerodynamic drag further modifies the dynamics of scattered planetesimals (Capobianco et al., 2011). For sufficiently large or small mono-dispersed planetesimals, the planet typically migrates inward. However, for a range of plausible planetesimal sizes (0.5–5.0 km at 5.0 au in a minimum mass Hayashi disk) outward migration frequently occurs, often accompanied by substantial mass accretion. Close and distant encounters have different dependencies on the surface density and eccentricity profiles, with viscous stirring of the planetesimal disk yield-

ing steady planet migration for a range of plausible conditions (Ormel et al., 2012; Kominami et al., 2016).

Young planetary systems with closely spaced orbits may have arrived in stable mean motion resonance configurations through interaction with the gas disk (§10.10.2). Following gas dispersal, the subsequent effects of planetesimal migration can lead to further large-scale dynamical instability, with more-or-less cataclysmic results (e.g. Thommes et al., 2008a). Planetesimal disk migration may therefore be an evolutionary step in many planetary systems. Some outcomes may resemble the architecture of the solar system, while others end up with high-eccentricity orbits.

Observational manifestations of planetesimal disks include the resulting collisional attrition responsible for debris disks observed around many stars (§10.6), and the zodiacal dust in the solar system (§12.5.13).

**Solar system** In the solar system, the existence of the Oort comet cloud, the Kuiper belt, and plausible inefficiencies in planetary core formation, all suggest that there was once a residual planetesimal disk of mass  $10 - 100M_{\oplus}$  in the vicinity of the giant planets following their formation. Since removal of this disk requires an exchange of orbital energy and angular momentum with the planets, significant planetary migration can follow (Hahn & Malhotra, 1999).

Indeed, there is good evidence for planetesimal-driven migration having had significant effects on the architecture of the solar system, and the mechanism by which the giant planets acquired their current orbits after the gas-disk dissipation (e.g. Gomes et al., 2004; Tsiganis et al., 2005; Murray-Clay & Chiang, 2006; Morbidelli & Levison, 2008). The detailed consequences of disk migration for the solar system, for which observational constraints are both numerous and detailed, in-



cluding the lunar Late Heavy Bombardment, the (unexpectedly small) mass of Mars, and the dynamical structure of the Kuiper belt, are considered in §12.6. Explanations for these types of complexities provides additional support for the paradigm of planet formation according to the solar nebula theory.

#### 10.10.4 Planet–planet scattering

Gravitational interactions between orbiting planets in the same system, resulting in *planet–planet scattering*, can continue as a result of intrinsic instabilities (arising from migration and resonances) both during, and often more significantly after, the gas and planetesimal disks have been lost or depleted (Weidenschilling & Marzari, 1996; Rasio & Ford, 1996; Levison et al., 1998; Barnes, 2010; Marzari, 2010; Lega et al., 2013).

During this evolutionary phase, evolution of an initially unstable multiple planetary system can undergo dramatic changes in orbital architecture, resulting in the ejection of one or more planets (typically the lightest), in an increased orbital separation tending towards a more stable configuration, or in planet–planet or planet–star collisions. The relative probability of these events is determined by the initial orbital radii, masses, and orbital eccentricities, and N-body experiments are needed to study the evolution of any given system. Scattering may be accompanied or stimulated by gas disk migration, and may be accompanied by Lidov–Kozai resonance enhancing eccentricity growth.

Modeling by Pfyffer et al. (2015) suggests that these dynamical interactions continue for  $\sim 100$  Myr after the dissipation of the protoplanetary disk, and are a necessary ingredient in bringing the eccentricities of planet populations in the Bernese planet formation model in line with observed distributions. At the same time, other characteristics such as the mass and semi-major axis distributions remain largely the same after 100 Myr as at the time of disk dispersal, implying that they are largely determined by the formation process alone.

Typically, the end result is a modest inward migration of the surviving planets, often with a significant gain in eccentricity. High-eccentricity planets with very large apocentric distances,  $\geq 10000$  au, also appear in these simulations, representing a transient phase on the path to ejection and the formation of ‘free-floating’ planets (e.g. Scharf & Menou, 2009; Veras et al., 2009; Bromley & Kenyon, 2014). The detection of such free-floating ejected planets may be possible through microlensing (§5.6), or perhaps through more exotic impact signatures on the horizontal branch in dense globular clusters (Soker et al., 2001).

Planet–planet scattering is a leading candidate for explaining the occurrence of non-circular orbits, with simulations reproducing the incidence and distribution of high orbital eccentricities amongst the most massive,

with tidal circularisation (or destruction) further modifying some close-in orbits.

Studies include: • the formation of high eccentricity and high inclination planets (Lin & Ida, 1997; Marzari & Weidenschilling, 2002; Sotiriadis et al., 2017); • ejected planets (Guillochon et al., 2011; Veras & Raymond, 2012); • the formation of close-in giant planets (Weidenschilling & Marzari, 1996; Nagasawa et al., 2008; Naoz et al., 2011; Beaugé & Nesvorný, 2012; Lai, 2012; Storch & Lai, 2014; Petrovich et al., 2014); • effects on obliquities (Albrecht et al., 2012b; Valsecchi & Rasio, 2014b); • the formation of close-in Earths (Ji et al., 2011); • the formation and distribution of wide-separation orbits (Levison et al., 1998; Veras et al., 2009; Scharf & Menou, 2009; Raymond et al., 2010); • the formation of compact systems (Raymond et al., 2009b); • implications for terrestrial planets (Veras & Armitage, 2005); • resulting mean motion resonances (Raymond et al., 2008a); • observational tests including eccentricity distributions (Barnes & Greenberg, 2007a; Ford & Rasio, 2008; Jurić & Tremaine, 2008); • and various other aspects including effects of disk torques, migration, and chaos (Rasio & Ford, 1996; Terquem et al., 1998; Ford et al., 2001a; Papaloizou & Terquem, 2001; Terquem & Papaloizou, 2002; Adams & Laughlin, 2003; Ford et al., 2003; Adams, 2004; Ford et al., 2005; Moorhead & Adams, 2005; Chatterjee et al., 2008; Moeckel et al., 2008; Thommes et al., 2008b; Raymond et al., 2009a; Matsumura et al., 2010b; Liu et al., 2011a; Wu & Lithwick, 2011; Schlaufman & Winn, 2013; Timpe et al., 2013; Pearce & Wyatt, 2014; Petrovich, 2015c; Pfyffer et al., 2015).

Amongst these, Pfyffer et al. (2015) concluded that this post-formation evolution remains insufficient to explain observed eccentricities, requiring the inclusion of additional sources of dynamical perturbation such as stellar fly-bys (§10.10.5), and Veras & Raymond (2012) concluded that planet–planet scattering alone cannot explain the free-floating planet population

A candidate for an extreme orbital period ratio outcome of planet–planet scattering is PTFO 8–8695 (CVSO 30; §6.19.5), a suggested 2-planet system (van Eyken et al., 2012; Schmidt et al., 2016), with periods 0.45 d (0.008 au) and 27 000 yr (660 au).

**Planet–planet with planetesimal scattering** Specific simulations which include the effects of both planet–planet scattering, and planetesimals disk interactions at larger orbital radii, have also been carried out (Raymond et al., 2009a, 2010). Their simulations follow the evolution of three massive planets, initially formed in marginally-unstable configurations (specifically, unstable over  $10^5 - 10^6$  yr), randomly separated by 4–5 mutual Hill radii, and orbiting up to 10 au. A planetesimal disk of total mass  $50M_{\oplus}$ , as used in the Nice model (§12.6), orbits between 10–20 au. Each of 5000 N-body simulations were integrated over 100 Myr with a 20-day time step. A selection of results is shown in Figure 10.37.

The picture which emerges from these and other numerical simulations is that the broad eccentricity distribution observed for large exoplanet masses ( $M_p \geq 0.3M_J$ ), which is primarily derived from planets at  $a \lesssim 3$  au, is consistent with the distribution arising from iso-

lated planet–planet scattering. For lower mass planets, the presence of the planetesimal disk results in a wide range of evolutionary behaviour, including strong orbital scattering, sudden jumps in eccentricity due to resonance crossings driven by divergent migration, and the strong damping of eccentricities for low-mass planets scattered to large orbital radii.

These simulations lend support to the hypothesis that the lower eccentricities observed for low-mass planets at large orbital radii reflect the past dynamical effects of residual planetesimal disks. Planetary inclinations with respect to the initial orbital plane, and the mutual inclination in multiple planetary systems, are damped in the same way as eccentricity.

The simulations also show that scattering leads to dynamically-packed systems, in which the final separations of two-planet systems cluster close to their Hill stability boundary. A measure of the proximity of a pair of orbits to the Hill stability boundary is given by the quantity  $\beta/\beta_{\text{crit}}$  (Barnes & Greenberg, 2006c; Raymond et al., 2010) for which the results of scattering simulations, and the observed values for known two-planet systems, are shown in Figure 10.37c.

**Scattering into resonances** Planet–planet scattering can also populate a variety of orbital resonances, including high-order mean motion resonances, up to 11th order in the simulations of Raymond et al. (2008a). Addition of the planetesimal disk acts as a damping force on the planetary orbits, further inducing mean motion resonances and even resonance chains (e.g. analogous to the 4:2:1 Laplace resonance in Jupiter’s Galilean satellites) with high efficiency (Raymond et al., 2009a).

For systems formed in more stable configurations, and not resulting in subsequent close planet–planet encounters, damping by the planetesimal disk also acts to align the orbits into mean motion resonances through convergent migration. A large fraction of outer high-mass giant planets might therefore be expected to orbit in resonance, especially if their orbits display the low-eccentricities expected of more stable systems.

Although the observed orbital arcs are limited in duration, stability analysis suggests that the wide-orbiting triple planet system HR 8799 may be the first example of such a resonant chain (Reidemeister et al., 2009; Fabrycky & Murray-Clay, 2010).

### 10.10.5 External gravitational perturbations

**Stellar fly-bys** Modification of planetary orbits and ejections, along the lines of planet–planet scattering, is also associated with perturbations by a passing (‘fly-by’) star (Zakamska & Tremaine, 2004; Malmberg et al., 2011; Boley et al., 2012b; Veras & Moekel, 2012; Marzari & Picogna, 2013; Picogna & Marzari, 2014; Veras et al., 2014; Correa-Otto & Gil-Hutton, 2017).

Effects may be particularly pronounced in star clusters (Laughlin & Adams, 1998; Bonnell et al., 2001; Smith & Bonnell, 2001; Fregeau et al., 2006; Spurzem et al., 2009; Thies et al., 2011; Parker & Quanz, 2012; Hao et al., 2013; Liu et al., 2013a; Pacucci et al., 2013; Li & Adams, 2015; Portegies Zwart & Jilková, 2015; Wang et al., 2015f; Cai et al., 2017, 2018). Encounters may also be relevant during the protoplanetary disk phase (Adams et al., 2006; Breslau et al., 2014; Vincke et al., 2015; Vincke & Pfalzner, 2016; Bhandare et al., 2016; Breslau et al., 2017; Wijnen et al., 2017b; Vorobyov et al., 2017).

Zakamska & Tremaine (2004) found that eccentricities can be excited in the outer parts of extended planetary disks by stars passing at a few 100 au. After the encounter, disturbances propagate inwards because of secular interactions in the disk, eventually exciting the inner planets. Over 5 Gyr, they estimated that typical eccentricities excited by field star encounters in the solar neighbourhood are in the range 0.01–0.1. Higher values ( $e \geq 0.1$ ) may be excited in planetary systems around stars formed in relatively dense, long-lived open clusters.

Malmberg et al. (2011) found that fly-bys can lead to the immediate ejection of planets, to the capture of one or more planets by the intruder, and more frequently to orbit perturbations, sometimes leaving the system in an unstable state. Over time-scales of a few Myr to several 100 Myr after fly-by, this can trigger planet–planet scattering, leading to the ejection of one or more planets. In the case of the four gas giants of the solar system, the fraction of systems from which at least one planet is ejected more than doubles in 100 Myr after the fly-by.

Finding similar inward propagating disturbances, Monte Carlo models by Hao et al. (2013) indicate that stellar encounters can account for the apparent scarcity of exoplanets in star clusters, not only for those on wide-orbit that are directly affected by stellar encounters, but also planets close to the star which can disappear long after the stellar encounter.

Statistics of stellar fly-by encounters with the solar system, in part based on astrometric measurements from Hipparcos and Gaia, are detailed in Section 12.1.6.

**Galactic tidal field** Related effects originate from interaction with the Galactic tidal field, especially in the inner regions of the Galaxy, and in particular via the re-configuration of wide binary orbits (Kaib et al., 2013; Veras & Evans, 2013a; Veras et al., 2014).

Perturbations scale inversely with Galactocentric radius, and so are much greater in the inner regions than in the solar neighbourhood. Over 3.5–10 kpc, vertical tides from the Galactic disk dominates, while interior to 3.5 kpc, due to the Galactic bulge, the in-plane and vertical components are comparable. Veras & Evans (2013a) found that the greatest perturbations occur when the planetary orbit is highly misaligned to the Galactic plane. When perpendicular,  $e_p$  is driven to unity (while  $a_p$  is secularly unaffected). The effect of Galactic tides is minimised when both planes are aligned, but remains non-zero.

The solar system’s invariable plane (§12.1.5) is itself misaligned with the Galactic plane by  $\sim 60^\circ$  (e.g. Huang & Wade, 1966; Duncan et al., 1987). Although the inclination of exoplanet orbits with respect to the Galactic plane is largely unconstrained (with no information from radial velocity measurements alone, and only line-of-sight inclinations of  $\sim 90^\circ$  from transit measurements alone), high inclinations certainly exist,

and may even be typical. More will be known with Gaia (§3.9).

Within a star's Hill surface, stellar gravity dominates, and an exoplanet will be largely unaffected by Galactic tides (e.g. Heisler & Tremaine, 1986). Exterior to the Hill surface, Galactic tides are always important. For a  $1M_{\odot}$  star in the solar neighbourhood, the Hill surface has an extent  $\sim 10^5(M/M_{\odot})^{1/3} \sim 100$  kau, which marks the boundary of the Oort cloud, and where Galactic tides play a key role in deflecting comets into the inner solar system (§12.5.7). The effect of Galactic tides on the solar system planets is negligible, even over its lifetime.

Deep within the Galactic bulge, inclinations of  $\sim 60^\circ$  would result in eccentric Neptunes (at  $\sim 30$  au) experiencing eccentricity variations of several tenths. Planets with the widest known separations ( $\sim 10^3$  au) would experience similar variations in the Galactic disk. Assuming simple circular Galactic orbits, these variations occur on time scales of a few Gyr.

### 10.10.6 Lidov–Kozai oscillations

**Context** Many binary star orbits are inferred to have decreased by 1–2 orders of magnitude since formation. Specifically, many main-sequence stars have companions at a few  $R_{\star}$ , far closer than predicted by star formation models. These compact binaries are often accompanied by a more distant (hierarchically-orbiting) tertiary, but with characteristics of the inner and outer binaries notably distinct from the general binary population (for details, see, e.g. Fabrycky & Tremaine, 2007).

A similar situation is encountered for exoplanet orbits: current theories of planet formation indicate that the region within 0.1 au of a protostar is too hot and rarefied for Jupiter-mass planets to form, yet many ‘hot Jupiters’ are found at these close-in distances.

Different orbit-shrinking mechanisms have been proposed, including migration in multiple star systems (e.g. Tokovinin, 2008), and planet–planet scattering during planetary formation (§10.7.1). A favoured theory in the case of close binary stars, which may also have produced at least a portion of hot Jupiters, is the combination of *Lidov–Kozai oscillations* with *tidal friction*.

The following description of the phenomenon of *Lidov–Kozai oscillations* (also known as *Kozai resonance*, *Kozai cycles*, and *Kozai migration*), builds on that by Fabrycky & Tremaine (2007). The additional effects of tidal friction are considered subsequently. A broad treatment is given by Shevchenko (2017b).

**Hierarchical stability** For three point masses interacting only through gravity, numerical investigations show that long-term stability typically requires that the system is hierarchical ( $a_{\text{out}} \gg a_{\text{in}}$ ), and that the eccentricity of the outer binary,  $e_{\text{out}}$ , cannot be too large, so that  $m_3$  (the outer) cannot make close approaches to  $m_1$  or  $m_2$  (the inner binary). An equivalent statement is that gravitational perturbations from  $m_3$  on the inner binary must be weak. However, even weak perturbations can have important long-term effects on the inner binary.

One of these long-term effects is precession of the inner binary's orbit plane, which occurs if the planes of

the inner and outer binaries are not aligned. If the inner and outer binary orbits are circular, both the mutual inclination and the scalar angular momenta remain fixed, while the two angular-momentum vectors precess around the direction defined by the total angular-momentum vector of the triple system.

**Nature of the oscillations** An unexpected effect in hierarchical triple systems was discovered by Kozai (1962) in the context of asteroid orbits, and independently by Lidov (1962) for artificial and natural satellite orbits.

If the inner binary orbit is initially circular, with a mutual inclination between inner and outer binaries  $i_0$ , there is a critical angle  $i_c$  such that if  $i_c < i_0 < 180^\circ - i_c$ , then the orbit of the inner binary does not remain circular as it precesses: both the eccentricity of the inner binary  $e_{\text{in}}$  and the mutual inclination  $i$  execute periodic oscillations, known as Kozai cycles.

In the (quadrupole) approximation in which the outer orbit is axisymmetric ( $e_{\text{out}} = 0$ ), and one of the inner components is a (massless) test particle, the  $z$ -component of the angular momentum of the inner and outer orbits is conserved (e.g. Innanen et al., 1997; Naoz, 2016), and

$$L_z \equiv \sqrt{(1 - e_{\text{in}}^2)} \cos i_{\text{in}} = \text{constant} . \quad (10.62)$$

As a result,  $e_{\text{in}}$  and  $i_{\text{in}}$  oscillate periodically and slowly, with higher eccentricity accompanying smaller inclinations, and *vice versa*, on a time scale much longer than the inner and outer orbital periods.

The amplitude of the oscillations in  $e_{\text{in}}$  and  $i_{\text{in}}$  are independent of the strength of the perturbation from the outer body, which depends on  $m_3$ ,  $a_{\text{out}}$ , and  $e_{\text{out}}$ , but the oscillation amplitude depends on  $i_0$ . Thus, for initial circular orbits with  $i_0 = i_c$  or  $180^\circ - i_c$ , the maximum eccentricity of the inner binary  $e_{\text{in,max}} = 0$ , but if  $i_0 = 90^\circ$ , then  $e_{\text{in,max}} = 1$ , and the two inner bodies collide.

Kozai cycles can be investigated analytically by averaging over the orbital phases of the inner and outer binaries, in which the semi-major axes of the inner and outer binary are both conserved (Kozai, 1962; Ford et al., 2000b). This time averaging, or *secular approximation*, is justified because the precession time is generally much longer than the orbital period of either binary.

In the limiting case when  $a_{\text{out}} \gg a_{\text{in}}$ , and the angular momentum of the outer binary is much greater than that of the inner binary, such that the orientation of the outer binary is a constant of the motion, the critical inclination is (Fabrycky & Tremaine, 2007)

$$i_c = \cos^{-1} \sqrt{3/5} = 39.2^\circ . \quad (10.63)$$

If the inner orbit is initially circular, the maximum eccentricity achieved in a Kozai cycle is

$$e_{\text{in,max}} = [1 - (5/3) \cos^2 i_0]^{1/2} . \quad (10.64)$$

Depending on initial conditions, the argument of pericentre  $\omega_{\text{in}}$  can either librate, or circulate (cf. §10.8).

The only property of the oscillation that depends on the masses, their semi-major axes, or  $e_{\text{out}}$  is the oscillation period, which is of order (Kiseleva et al., 1998)

$$\tau = \frac{2P_{\text{out}}^2}{3\pi P_{\text{in}}} \frac{m_1 + m_2 + m_3}{m_3} (1 - e_{\text{out}}^2)^{3/2}. \quad (10.65)$$

For a triple system in which the semi-major axis  $a_{\text{out}}$  of the outer binary increases, while its mass, inclination, and eccentricity remain constant, the maximum eccentricity of the inner binary will remain fixed, but the period of the Kozai cycle will grow as  $a_{\text{out}}^3$ . This behaviour will continue so long as the perturbation from the outer body is the dominant cause of apsidal precession in the inner binary. Thus, weak perturbations from a distant third body can induce large oscillations in  $e_{\text{in}}$  and  $i_{\text{in}}$ .

Additional sources of apsidal precession in the inner binary (including general relativity, tides, quadrupole moments, and planetary companions; cf. §6.19.4) can suppress Kozai oscillations caused by a distant third body if they dominate the apsidal precession.

**Higher-order effects** Various higher-order effects have been studied (e.g. Kinoshita & Nakai, 1999, 2007; Malmberg et al., 2007a; Katz et al., 2011; Lithwick & Naoz, 2011; Libert & Delsate, 2012; Naoz et al., 2013a,b; Naoz, 2016; Storch et al., 2017).

Such systems are often studied using perturbation theory to write the Hamiltonian of a hierarchical three-body system as a sum of two terms responsible for the isolated evolution of the inner and the outer binary, and a third term coupling the two orbits. The coupling term is conveniently expanded in terms of  $\alpha = a_{\text{in}}/a_{\text{out}}$  (Naoz et al., 2013a). For plausible systems, the perturbative series converges rapidly, and the qualitative behaviour of a hierarchical three-body system is determined by the initial terms in the expansion, viz. the quadrupole ( $\propto \alpha^2$ ), octupole ( $\propto \alpha^3$ ), and hexadecapole ( $\propto \alpha^4$ ) expansions. For many systems, a satisfactory description is given by the lowest, quadrupole expansion, although the octupole term becomes dominant in certain regimes, and is responsible for a long-term variation in the amplitude of the Lidov–Kozai oscillations.

Relaxing the (quadrupole) approximation of an axisymmetric (circular) outer orbit, and for an inner massless test particle,  $j_z$  (Equation 10.62) is no longer a constant of the motion, and somewhat different behaviour results. In this higher-order (octupole) approximation (Ford et al., 2000b; Naoz, 2016),  $e_{\text{in}}$  can reach very high values, albeit ill-defined since the system is generally chaotic (Ford et al., 2000b; Naoz et al., 2013a; Teysandier et al., 2013a; Li et al., 2014b,c; Liu et al., 2015a).

In addition, and with respect to the total angular momentum, the inner orbit can flip from prograde to retrograde, an effect referred to as the *eccentric Lidov–Kozai mechanism* (Naoz et al., 2011; Li et al., 2014c; Luo et al., 2016; Naoz et al., 2017).

**Interior perturber** The Lidov–Kozai resonance describes the behaviour of an interior test particle in the secular three-body problem. The ‘inverse’ secular problem, involving an exterior test particle and an *interior* perturber, has been less well studied, but has potential application to systems such as the Kuiper belt, debris disks, and circumbinary planets.

In the context of Kuiper belt objects perturbed by Neptune and the other giant planets, Gallardo et al. (2012) discovered

an analogous Lidov–Kozai resonance for this inverse problem, in which the argument of pericentre  $\omega_{\text{out}}$  librates about either  $+90^\circ$  or  $-90^\circ$  when  $i \sim \cos^{-1}(1/5) \sim 63^\circ$ . In their study of the inverse problem, Naoz et al. (2017) expanded the potential to octupole order for non-zero  $e_{\text{in}}$ , and identified orbit-flipping via a quadrupole-level resonance, as noted above.

Vinson & Chiang (2018) expanded to hexadecapole order, and identified four secular resonances, confirmed in N-body simulations: (i) an orbit-flipping quadrupole resonance requiring a non-zero perturber eccentricity  $e_{\text{in}}$ ; (ii) a hexadecapole ‘inverse Kozai’ resonance for perturbers that are (nearly) circular, and inclined by  $i \sim 63^\circ/117^\circ$ , and which can lead to orbit crossings; (iii) an octupole ‘apsis-aligned’ resonance at  $i \sim 46^\circ/107^\circ$ ; and (iv) an octupole resonance at  $i \sim 73^\circ/134^\circ$ .

Qualitatively, the more eccentric the perturber, the more the outer test particle’s eccentricity and inclination vary, with more polar orbits also being more chaotic.

**Kozai cycles with tidal friction** As a result of the perturbation from a highly inclined tertiary in a hierarchical triple, the Lidov–Kozai mechanism allows wide-orbiting systems to be driven into close pericentre approaches. Pericentres of a few  $R_\star$  can result in significant orbital energy loss due to tidal dissipation (and, perhaps, gravitational radiation), reducing  $a_{\text{in}}$  and further enhancing dissipation, until the inner binary settles into a circular orbit with  $a_{\text{in}} \sim \text{few } R_\star$ . Pericentre collapse is halted when tidal friction circularises the orbit faster than the Kozai torque can excite it. Models can replicate hot Jupiters with a peak of  $a_{\text{in}} \sim 3 \text{ d}$  (Wu et al., 2007).

The combined process is referred to as *Kozai cycles with tidal friction* (Harrington, 1968; Mazeh & Shaham, 1979; Kiseleva et al., 1998; Eggleton & Kiseleva-Eggleton, 2001; Eggleton & Kiseleva-Eggleton, 2006; Fabrycky & Tremaine, 2007).

The final product is a triple system with a large ratio  $P_{\text{out}}/P_{\text{in}}$ , a circular inner orbit,  $e_{\text{in}} \sim 0$ , and a mutual inclination often near the critical value,  $i \sim i_c$ . The distinctive inclination distribution (Fabrycky & Tremaine, 2007, their Figure 7b) may provide the strongest observational evidence for this process, if the inclination persists to the present. Fabrycky & Tremaine (2007) identified three mechanisms which may subsequently modify the mutual inclination (Galactic tide, individual passing stars, and stellar spin precession) but argued that each is negligible, such that the final mutual inclination indeed persists after completion of tidal circularisation.

**Application to stellar systems** Applied to stellar systems, the first (theoretical) investigations of Lidov–Kozai oscillations were made by Harrington (1968, 1969), Mazeh & Shaham (1979), and Söderhjelm (1982). A higher, third-order theory was given by Ford et al. (2000b), and used to explain the configuration of the triple system Algol (Kiseleva et al., 1998).

Amongst subsequent work, the simulations of Fabrycky & Tremaine (2007) concluded that the combined process can produce most close binaries (although, as detailed below, not *most* hot Jupiters). Supporting this hypothesis is the fact that almost all close binaries, with  $P_{\text{orb}} \leq 3 \text{ d}$ , have a tertiary companion (Tokovinin et al., 2006). A class of high-eccentricity eclipsing

binaries, discovered with Kepler, may represent a stellar population undergoing this type of evolution (Dong et al., 2013b; Anderson et al., 2017b).

Lidov–Kozai oscillations play a key role in the evolution of various other hierarchical three-body systems, and continuing attention is being given to the effect in stellar binaries (e.g. Wu et al., 2007; Naoz et al., 2012); in star clusters (e.g. Parker & Goodwin, 2009); in protoplanetary disks (e.g. Teyssandier et al., 2013b; Martin et al., 2014; Teyssandier & Ogilvie, 2016; Fu et al., 2017b; Zanazzi & Lai, 2017b), in black hole mergers (e.g. Blaes et al., 2002), and in white dwarf–white dwarf mergers and the production of supernova Ia (Thompson, 2011; Katz et al., 2011; Katz & Dong, 2012; Shappee & Thompson, 2013).

**Application to exoplanets** There are two orbital characteristics that have been considered (partially) explainable, initially by Kozai oscillations alone, and subsequently combined with tidal friction: the existence of very large eccentricities (up to  $e = 0.96$  for HD 20782), and the existence of hot Jupiters.

Before the appreciation of the role of tidal friction, the large eccentricities found in a number of the early discoveries, such as 16 Cyg B ( $e = 0.69$ ), led to the speculation that they could be explained by Kozai cycles if the host star was a member of a binary system (Mazeh et al., 1997; Innanen et al., 1997; Holman et al., 1997). However, this hypothesis led to two predictions that were not verified: that high-eccentricity planets should mostly be found in binary systems, and that multi-planet systems should have low eccentricities since their mutual apsidal precession would suppress the Kozai cycle (Tremaine & Zakamska, 2004; Takeda & Rasio, 2005).

Even under the hypothesis that every exoplanet host had an undetected stellar companion, Takeda & Rasio (2005) showed that Kozai cycles alone could not explain the distribution of observed eccentricities, although many of the planets with the largest eccentricities orbit stars with companions (Wright et al., 2011b).

Kozai cycles combined with the effects of tidal friction was invoked to explain the presence of hot Jupiters by Kiseleva et al. (1998). Wu & Murray (2003) applied it to HD 80606 b, with its very large eccentricity ( $e = 0.93$ ) and small pericentre distance,  $q = a(1 - e) = 0.033$  au. Fabrycky & Tremaine (2007) showed that the resulting hot Jupiters generally have orbital angular momentum misaligned with the stellar spin axis by large angles, frequently larger than  $90^\circ$ .

The combined mechanism has also been invoked to explain, for example, the retrograde orbit of HAT-P-7 b (Narita et al., 2009b); the high eccentricity of GJ 436 b (Beust et al., 2012); and the orbits of HD 106515A b and HD 196067 b (Marmier et al., 2013).

Other considerations of Lidov–Kozai oscillations in exoplanet (and protoplanetary) systems, and more complex configurations, continue to be explored (e.g. Libert & Tsiganis, 2009a; Terquem & Ajmia, 2010; Funk et al., 2011a; Libert et al., 2011; Nagasawa & Ida, 2011; Tamayo et al., 2013; Martí & Beaugé, 2015; Anderson et al., 2016;

**Lidov–Kozai oscillations in the solar system:** The solar system giant planets are accompanied by over 100 small ‘irregular’ satellites (§12.5.10). None are found with  $55^\circ < i < 130^\circ$  (relative to the ecliptic), although prograde orbits with smaller inclination and retrograde orbits with larger inclination are common. The gap is explained by Lidov–Kozai oscillations: at  $i \sim 90^\circ$  the oscillations are such that the satellite either collides with one of the larger regular satellites or the planet at pericentre, or escapes from the planet’s gravitational field at apocentre (Carruba et al., 2002; Nesvorný et al., 2003).

The effect is also relevant in the survival of the outer planetary satellites (Kinoshita & Nakai, 1991), in the orbital evolution of satellites of Kuiper belt objects due to perturbations from the Sun (Perets & Naoz, 2009; Naoz et al., 2010), in near-Earth binary asteroids (e.g. Fang & Margot, 2012c), and in extreme trans-Neptunian objects (e.g. de la Fuente Marcos & de la Fuente Marcos, 2014).

In the presence of Lidov–Kozai oscillations, satellites in low Earth orbit are largely stable because of a fortuitous property of the Earth’s dominant quadrupole moment,  $J_2$  (Tremaine & Yavetz, 2014).

Lidov (1962) pointed out that if the inclination of the lunar orbit was changed to  $90^\circ$  to the ecliptic, with all other orbit elements retained, such a ‘vertical Moon’ would collide with the Earth in  $\sim 4$  yr as a result of a Lidov–Kozai oscillation induced by the gravitational field of the Sun.

Carvalho et al., 2016; Ali-Dib, 2017; Becker et al., 2017b; Hamers et al., 2017; Hamers, 2017b; Hamers & Lai, 2017; Mustill et al., 2017; Nelson et al., 2017).

Amongst these are studies assessing associated formation and survival prospects during planet formation (Batygin et al., 2011b; Chen et al., 2013b; Giuppone & Leiva, 2016; Martin et al., 2016b; Muñoz et al., 2016), and the contribution of Lidov–Kozai oscillations to the chaotic evolution of the stellar obliquity, depending on the planet mass and the stellar rotation rate, and hence the observed spin–orbit misalignments (Storch et al., 2014; Storch & Lai, 2015b). In the latter case, inclusion of the effects of tidal decay of the planetary orbit leads to a gradual (resonantly trapped) evolution of the spin–orbit alignment, termed *adiabatic resonance advection*.

**Systems in Kozai resonance** For five multi-planet systems not in mean motion resonance, Libert & Tsiganis (2009a) used a parametric study, verified by secular theory, to show that four ( $\nu$  And, HD 12661, HD 74156, and HD 169830) are consistent with a stable (non-circular) Kozai-resonant state, if their (unknown) mutual inclinations are  $\Delta i \sim 45^\circ$ .

**Hot Jupiter companions** Highly eccentric giant planets destined to become hot Jupiters through tidal circularisation will, during their Gyrs of shrinking apocentres, generally clear out any low-mass inner planets in the system, but may also lead to ejection of the giant planet, or to a giant planet with moderately high eccentricities with  $a \lesssim 1$  au, a region otherwise hard to populate (Mustill et al., 2015). Although this may explain the gen-

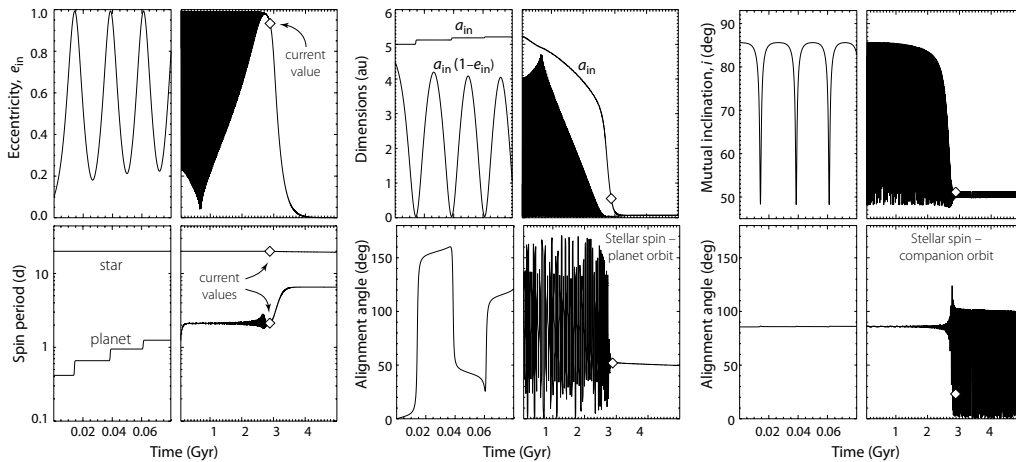


Figure 10.38: Evolution of a hypothetical progenitor to HD 80606 b ( $e = 0.932$ ) from the simulations of Kozai cycles with tidal friction by Fabrycky & Tremaine (2007), with two time scales for each parameter. The planet is initially in an orbit with  $a_{\text{in}} = 5$  au,  $i = 85^\circ.6$ ,  $e_{\text{in}} = 0.1$ ,  $\omega_{\text{in}} = 45^\circ$ . The spins of both planet and host star were initialised with zero obliquity. The stellar companion has  $m_3 = 1.1 M_\odot$ ,  $a_{\text{out}} = 1000$  au, and  $e_{\text{out}} = 0.5$ . Energy dissipation is dominated by the planet. Diamonds mark the current position of HD 80606 b in this possible evolution. From Fabrycky & Tremaine (2007, Figure 1), by permission of IOP Publishing/AAS.

eral lack of such companions to hot Jupiters (§6.28.5), statistics from radial velocity measurements are harder to reconcile (Schlaufman & Winn, 2016).

**Warm Jupiters** Warm Jupiters, with  $a \sim 0.1 - 1$  au ( $P \geq 10$  d), are also generally considered to orbit too near to their host to have formed *in situ*, although such models remain the subject of ongoing investigation (§6.28.5). With typically moderate eccentricity,  $e = 0.2 - 0.7$ , they are distant enough to retain a significant eccentricity in the face of tidal damping. It has been suggested that they may be migrating due to Lidov–Kozai oscillations, during which they migrate preferentially in the high-eccentricity phase of the oscillation, but are typically observed at lower eccentricities (Frewen & Hansen, 2016; Petrovich & Tremaine, 2016). Alternatively, their eccentricities may have been increased by secular interactions with exterior giant companions, following migration on a circular orbit (Anderson & Lai, 2017).

Petrovich & Tremaine (2016) hypothesised that their absence around stars with  $R \gtrsim R_\odot$  can be attributed to stellar evolution: as the host evolves, such planets would be rapidly engulfed at minimum pericentre, leading to their significant depletion with increasing  $R_\star$ . Petrovich & Tremaine (2016) showed that the underlying periodic migration leads to a steady-state eccentricity distribution which is approximately flat, in agreement with that of warm Jupiters with detected outer companions.

An alternative model attempts to place the formation of hot and warm Jupiters in a unified scheme, taking into account the fact that hot Jupiters tend to occur in isolation, while warm Jupiters more often have close-in, co-transiting companions (§6.28.5). Spalding

& Batygin (2017) suggested that both classes may arise via early migration or *in situ* conglomeration, but that the enhanced isolation of hot Jupiters arises due to a secular resonant interaction with the stellar quadrupole moment. Such an interaction tilts the orbits of exterior, lower-mass planets, removing them from transit surveys where the hot Jupiter is detected. Warm Jupiter-hosting systems, in contrast, retain their coplanarity due to the weaker influence of the host star’s quadrupolar potential relative to planet–disk interactions.

**Overall importance** In simulations of the formation of close binary stars and hot Jupiters (see Figure 10.38), Fabrycky & Tremaine (2007) concluded that Lidov–Kozai oscillations with tidal circularisation can produce most close binaries, and some *but not most*, hot Jupiters (the same conclusion was reached by, e.g., Crida & Batygin, 2014; Petrovich, 2015b; Antonini et al., 2016). There are two reasons: first, systems with one planet orbiting a star of a binary system (i.e., those for which such cycles are likely) have a planetary period distribution that is indistinguishable from other systems. Second, the limited information on spin–orbit alignment suggests that most host spins and planetary orbits are aligned, contrary to simulation results. For an individual binary star system hosting a transiting planet, however, large misalignment detected by the Rossiter–McLaughlin effect (§6.18) would constitute evidence for Kozai cycles with tidal friction *in that system*. A model enhancing the numbers of hot Jupiters generated in the case of wide-separation stellar binaries invokes the presence of a second giant planet orbiting the proto-hot Jupiter at several tens of au (Hamers, 2017a).

**Predictions** The simulations of Kozai cycles with tidal friction by Fabrycky & Tremaine (2007) give specific predictions on the mutual inclination of the inner and outer binaries, on the spin–orbit misalignment, and on the period distribution for hot Jupiters, viz., peaking at a few days, and with a minimum at longer periods ( $\sim 10$  d) for which tidal circularisation becomes ineffective.

Measurements of significant (sky-projected) misalignments between the stellar rotation axis and a planet’s orbital axis via the Rossiter–McLaughlin effect have been frequently reported as being consistent with the predictions of Kozai cycles (Section 6.18.8).

Socrates et al. (2012) argued that, in a steady state, the mechanism would result in a population of super-eccentric ( $e > 0.9$ ) migrating Jupiters with long orbital periods and small pericentres,  $q \sim \text{few } R_*$ , and a number distribution satisfying  $dN/d\log a \propto a^{1/2}$ . If this process produces most hot Jupiters, the Kepler sample should include several super-eccentric migrating progenitors of hot Jupiters, not yet tidally circularised. A significant Kepler population has not been found (Dawson et al., 2015b), again suggesting that the process is responsible for at most some, but not all, hot Jupiters.

### 10.10.7 Origin of large stellar obliquities

The large obliquities observed in a number of systems are typically attributed to planet–planet scatterings or other secular interactions between multiple planets (§10.10.4), or Lidov–Kozai effects induced by a distant companion (§10.10.6). Various other contributions have also been considered.

Various authors have considered a ‘primordial origin’ for (at least part of) the observed spin–orbit misalignments, originating from a misalignment between the stellar spin and the protoplanetary disk (Bate et al., 2010a; Thies et al., 2011; Batygin, 2012; Lai, 2014; Spalding & Batygin, 2014; Fielding et al., 2015).

Lai (2014) summarises the evidence for this suggestion, appealing to the configuration observed in the solar system (see also Section 12.1.5), misalignment of the rotation axis observed in some main sequence binaries, misaligned disks in some binary young stellar objects, and the evidence for misalignment in the case of a number of co-planar multi-planet systems, including Kepler–9 (Walkowicz & Basri, 2013), Kepler–56 (Huber et al., 2013a), and others (Hirano et al., 2014).

Several mechanisms have been identified for tilting a star relative to its protoplanetary disk to produce such a ‘primordial misalignment’. These include (Lai, 2014): more chaotically accreting gas, such that the stellar spin direction can be different from the disk orientation at later accretion phases (Bate et al., 2010a); encounters between a protostellar system and another disk/envelope system with a different direction of rotation, especially in stellar clusters (Thies et al., 2011; Win-

ter et al., 2018a); magnetic star–disk interactions (Lai, 1999; Lai et al., 2011); varying orientations of outer disks and warps (Foucart & Lai, 2011; Terquem, 2013; Xiang-Gruess & Papaloizou, 2013); disk precession driven by the gravitational torque from an inclined binary companion (Batygin, 2012; Batygin & Adams, 2013; Lai, 2014); and interaction between the protoplanetary disk and supernova ejecta (Wijnen et al., 2017a).

Asymmetric bipolar outflows in protostars may also incite orbital tilts in planet orbits (Veras et al., 2013a). Resonant momentum loss from a variable protostellar jet with periodic polarity reversal has been suggested as a contributor to Jupiter’s obliquity (Namouni, 2013).

More speculatively, Rogers et al. (2012) suggested that the observed stellar obliquities may result from the torques of varying directions deposited on the radiative stellar envelope by internally generated gravity waves. In this scenario, the photosphere would be rotating in a different direction from the interior.

## 10.11 Tidal effects

### 10.11.1 Relevance of tides

**Context** Three main processes are considered to deliver planets to close-in orbits such that star–planet tidal effects become significant: gas disk migration (§10.10.2), planet–planet scattering (§10.10.4), and Lidov–Kozai resonance (§10.10.6). These sub-populations are likely to have different distributions of eccentricity and obliquity.

The gravitational interaction between such resulting proximate (extended) bodies differs from that between point masses. Tidal forces result from the varying gravitational field over one or both bodies, and lead to deformation of their shape (which may be further modified by rotation), to energy dissipation, and to orbits which then evolve irreversibly, in size and shape. Tides are generated both on the planet due to the potential of the star, and on the star due to the planet.

The study of gravitationally-induced tides embraces both celestial mechanics and fluid dynamics, and has a long and involved history (e.g. Cartwright, 1999; Deparis et al., 2013). More recent theoretical work has been stimulated by the discovery of the very short-period hot Jupiters, as well as by gravitational wave research.

Given the present observational data, the focus here is on close-in giant planets which, like stars, are wholly or largely fluid, rather than terrestrial bodies, which are predominantly solid, although deformable. Nevertheless, the distinction is not absolute: giant planets may contain solid cores, and terrestrial bodies may contain oceans and atmospheres with significant tides.

Various reviews of exoplanet tidal phenomena have been made (Jackson, 2010; Mathis et al., 2013; Souchay et al., 2013; Tokieda, 2013; Ogilvie, 2014). The latter

provides the mathematical treatment necessary to understand the many manifestations of tidal interactions, used as the basis for some of the following framework.

**Overview** For close-in planets orbiting within about  $a \sim 0.2$  au of their host star, tidal forces eventually lead to alignment of their rotation axes, synchronisation of their rotation and orbital periods, a reduction in orbital eccentricity, an accompanying reduction in semi-major axis, and a conversion of orbital energy into tidal heating of the planet. The associated time scales for *tidal circularisation* are believed to be very long, of order 1 Gyr, but nonetheless with very significant effects on the planet's orbit and its thermal heating.

The fact that tidal dissipation plays a role in the organisation of planetary systems has been clear since the first detections of extrasolar planets. The relative absence of eccentric orbits (common at larger separations) with small pericentres suggests that tidal circularisation must take place for planets with  $P \lesssim 4$  d.

It is possible that the various mechanisms responsible for generating large orbital eccentricities is less effective for close-in systems. But the current view is that the observed decrease of eccentricities with decreasing  $a$  arises partly as a result of damping accompanying inward migration during the few Myr before gas disk dispersal (§10.10.2), with tides raised between close-in planets and their host stars further contributing to circularisation for systems within  $a \lesssim 0.2$  over the subsequent few Gyr (e.g. Rasio et al., 1996; Lubow et al., 1997; Marcy et al., 1997; Jackson, 2010).

The very long time scales involved in some tidal phenomena imply a clear distinction between the configurations that are currently observed on the one hand, and the possible endpoints of such tidal evolution on the other. Final equilibrium states are considered in Section 10.11.4, where it will be seen that only a subset of systems reach a final equilibrium state, with the others destined for destruction. No moons in the solar system, for example, will survive indefinitely, but rather only over the Gyr time scales on which they evolve.

### 10.11.2 Tidal amplitudes

Following Ogilvie (2014), and with body 1 denoting that in which the tide is raised, and body 2 being that which induces the tide (Figure 10.39), the dominant tidal interaction is usually between the gravitational quadrupole moment of body 1, and the monopole moment of body 2 (considered as a point mass). The monopole field of body 2 varies over the volume of body 1, creating a tidal field that is aligned with the axis joining their centres. This tidal field deforms body 1, generating a quadrupole moment. In the simplest case a spheroidal bulge, aligned with the axis, gives rise to a net attractive force in that radial direction.

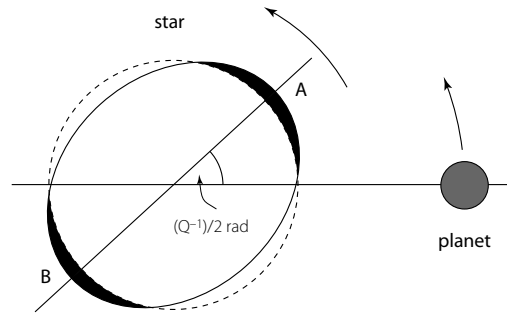


Figure 10.39: The force of attraction between an orbiting planet and the nearer tidal bulge on the star A exceeds that between the planet and B; the net torque retards the rotation of the star and accelerates the planet in its orbit, transferring angular momentum and energy from the star's rotation into the planet's orbital revolution. For a planet in an eccentric orbit, the tidal torque is larger at pericentre, but whether the net change in orbital eccentricity is positive or negative depends on the balance of tidal torques and radial forces, which in turn depends on the stellar rotation compared with the planet's orbital rotation. Adding the effects of tides raised on the planet by the star typically results in a decrease in orbital eccentricity.

An estimate of the tidal deformation is given by the (dimensionless) *tidal amplitude parameter*

$$\epsilon = \left( \frac{M_2}{M_1} \right) \left( \frac{R_1}{d} \right)^3 = \left( \frac{GM_2 R_1}{d^3} \right) / \left( \frac{GM_1}{R_1^2} \right), \quad (10.66)$$

where  $R_1$  is the (mean) radius of body 1, and  $d$  is the orbit separation. The second form shows that  $\epsilon$  is the ratio of the tidal gravity due to body 2 (at the surface of body 1), to the gravity of body 1; it is also an estimate of the ratio of the tidal height compared to  $R_1$ .

Equation 10.66 shows that tidal interactions are strongly dependent on the separation of the bodies in comparison with their sizes. Unless noted otherwise, the following describes situations for which  $\epsilon \ll 1$ . In more extreme situations, significant mass loss can result from Roche-lobe overflow, and tidal disruption can occur for planets scattered close to their host stars (§6.14.21).<sup>6</sup>

For exoplanets, particularly large tidal amplitudes (Equation 10.66) are inferred for the tide raised in the

<sup>6</sup> Ogilvie (2014) provides the following glossary: *tidal potential*: the part of the potential due to body 2 that deforms body 1; *tidal component*: a single spherical harmonic component of the tidal potential; *tidal torque*: rate of angular momentum transfer from the orbit to the spin of body 1; *tidal power*: rate of energy transfer; *tidal quality factor, phase lag, time lag*: alternative parameterisations of the tidal response functions; *equilibrium tide*: hydrostatic approximation to perturbations of density and pressure; *dynamical tide*: tidal response satisfying the time-dependent equations of fluid dynamics, usually including internal waves; *tidal equilibrium*: double synchronous state in which two bodies have a circular orbit with synchronised, aligned spins and no further tidal evolution occurs.



star WASP-18,  $\epsilon \sim 2 \times 10^{-4}$  (Hellier et al., 2009a), and for the tide raised in the planet WASP-19 b,  $\epsilon \sim 6 \times 10^{-2}$  (Hebb et al., 2010).

**Other systems** Tidal dissipation and evolution is relevant for many regular satellites of the other solar system planets, which display numerous complex phenomena (Peale, 1999), and provide various constraints on their tidal histories (Ogilvie, 2014, Section 5.4). For the solar system giants, the largest tidal amplitudes are  $\epsilon \sim 2 \times 10^{-7}$  (Jupiter, due to Io),  $3 \times 10^{-8}$  (Saturn, due to Titan),  $4 \times 10^{-8}$  (Uranus, due to Ariel) and  $8 \times 10^{-8}$  (Neptune, due to Triton).

Tides are also relevant to binary stars of all evolutionary stages, whenever the ratio of orbit separation to stellar radius is sufficiently small. They are central in describing gravitational radiation from merging double-degenerate binary stars (e.g. Kochanek, 1992; Bildsten & Cutler, 1992), for which relativistic tidal effects have been formulated (Binnington & Poisson, 2009).

### 10.11.3 Tidal dynamics

**Quality factor and phase lag** Early analysis of the tidal interaction between Earth and the Moon (Darwin, 1879b, 1880) was based on the concept of an *equilibrium tide*, in which a homogeneous spherical body continually adjusts to maintain a state of quasi-hydrostatic equilibrium in the varying gravitational potential of its orbiting companion. Darwin introduced a phase lag into the response (Figure 10.39), proportional to the tidal forcing frequency and attributable to the body's viscosity. This 'classical theory of tides' is based on the idea that the effect of dissipation is to cause the tidal response to lag behind the forcing with a constant time-lag, with the phase lag giving rise to a net tidal torque, and to a dissipation of energy. This remains the framework used for most tidal studies; the distinction between 'equilibrium tides' and 'dynamical tides' is noted in Section 10.11.6.

Subsequent formulations (e.g. Munk & MacDonald, 1960; Goldreich & Soter, 1966; Alexander, 1973; Hut, 1981) parameterised the efficiency of the tidal dissipation, whatever its origin, by a dimensionless *specific dissipation function* or *Q-value* (or quality factor), generally referred to as the *tidal quality factor*. As a measure of the departure of a tidally-distorted body from perfect elasticity or fluidity, this is defined by (e.g. Goldreich & Soter, 1966, eqn 1)

$$Q^{-1} = \frac{1}{2\pi E_0} \oint \left( -\frac{dE}{dt} \right) dt, \quad (10.67)$$

where  $E_0$  is the maximum energy stored in the tidal distortion, and the integral over  $-dE/dt$ , the rate of dissipation, is the energy lost during one orbit.

Although, in principle,  $Q$  is an unknown function of the frequency and amplitude of the tidal forcing, in

**Earth tides:** The most familiar example of tides is the Earth–Moon system, in which the Sun also plays a role. A vast literature, on both internal and ocean tides, extends to the work of Kepler, Galileo, Newton, Laplace, Darwin, Thomson, and others. Tidal dissipation, dominated by an ocean layer only 0.02% of Earth's total mass, leads to a lengthening of both day and month as angular momentum is transferred from the planetary spin to the orbit.

In outline, the tidal response of an oceanless Earth is approximated by assuming an *SNREI model* (Spherical, NonRotating, Elastic, and Isotropic; such that that elastic properties vary only with depth, as in normal-mode seismology), and the effects of ocean tides are added subsequently (Agnew, 2007). Assuming that tidal forcing has a much longer period than any normal mode (the longest for such an Earth have  $P < 1$  h), quasi-static harmonic theory restricts models to the equilibrium response.

By symmetry, only the degree  $l$  is then relevant, and the Earth's elastic response is then characterised by the dimensionless *Love numbers*  $k_l$ ,  $h_l$ ,  $l_l$  (Love, 1911, although  $l$  was only introduced by T. Shida in 1912), and where the subscript  $l$  refers to the harmonic degree (see the more general formulation in §10.11.3): for a surface potential  $V(\theta, \phi)/g$ , tidal distortion produces an additional gravitational potential  $k_l V(\theta, \phi)$ , a radial (vertical) displacement  $h_l V(\theta, \phi)/g$ , and a horizontal displacement  $l_l \nabla_1 V(\theta, \phi)/g$ . Magnitudes depend on the body's rigidity and mass distribution, and are zero for a rigid body.

For the modern standard 1d Earth model (PREM, Preliminary Reference Earth Model; Dziewonski & Anderson, 1981), the second-degree potential ( $l = 2$ ) is characterised by  $h_2 = 0.6032$ ,  $k_2 = 0.2980$ ,  $l_2 = 0.0839$  (Agnew, 2007).

Accounting for precession, nutation, and perturbations due to figure and planetary terms, the tide-generating potential of Doodson (1921) already distinguished 388 tidal frequencies. Some 60 are of sufficient size to be used in marine tide prediction, with complexities driven by their incommensurate frequencies. An illustrative java application is at <http://www.ams.org/samplings/feature-column/fcarc-tidesiii3>

planetary science it is usually treated as a constant property of each body in the solar system, corresponding to a constant *phase lag*, arcsin  $Q^{-1}$  (e.g. Murray & Dermott, 2000, Section 4.9). Studies of the Earth's rotation provide evidence that its  $Q$ -value is approximately constant over a wide range of frequency (Munk & MacDonald, 1960), even though a variety of mechanisms may be responsible. Earth's tidal  $Q$ -value may be predominantly determined by turbulent dissipation in the shallow seas (Ogilvie & Lin, 2004).

Dissipative processes (tidal friction) in each body result in a phase lag between the forcing potential and the body's deformation. If the planet's orbit period is longer than the star's rotation period, the lagging tide is carried ahead of the planet by an angle  $(Q^{-1})/2$  rad (MacDonald 1964 eqn 130; Goldreich & Soter 1966 eqn 2). It is the asymmetrical alignment of the tidal bulges with respect to the line of centres (Figure 10.39) which introduces a net torque between the two bodies.

As observed in close binaries (e.g. Mazeh, 2008), these torques act to align the rotation axes, synchronise their rotation and orbital periods, and circularise their orbits. The final effect on close-in planetary orbits, however, depends on the balance of tidal torques and radial forces, and the combined effects of the separate tides raised on the two bodies, as described further below.

In the solar system, tides are raised on the Sun by the planets and their satellites, on the planets by their satellites and the Sun, and on the satellites by the planets and the Sun. Darwin (1908) developed the tidal disturbing function into Fourier components, and derived expressions for the corresponding orbital evolution. Jeffreys (1961) indicated how tides raised on planets by satellites would usually cause a secular *increase* in orbital eccentricity. Goldreich (1963) showed that tides raised on satellites tend to decrease eccentricity, and may often counteract the effect of tides raised on the planet.

**Tidal potential** The complete tidal potential in a non-rotating frame can be written (Ogilvie, 2014, eqn 3)

$$\Psi = \text{Re} \sum_{l=2}^{\infty} \sum_{m=0}^l \sum_{n=-\infty}^{\infty} \frac{GM_2}{a} A_{lmn} \left(\frac{r}{a}\right)^l Y_l^m(\theta, \phi) e^{-in\Omega_0 t} \quad (10.68)$$

where  $\Omega_0 = (GM/a^3)^{1/2}$  is the mean orbital angular velocity (or ‘mean motion’, §2.1.1). Integers  $l$  and  $m$  are the degree and order of the spherical harmonic, with  $n$  denoting temporal harmonics of the orbital motion.

The complex coefficients  $A_{lmn}$  are involved functions of  $e$  and  $i$ . If the bodies are sufficiently separated, the quadrupole components ( $l = 2$ ) dominate. For a circular co-planar orbit,  $n = m$ , with  $l - m$  even. For a circular inclined orbit,  $-l < n < l$ , with  $l - n$  even. As  $e \rightarrow 1$ , and as a result of the sensitivity of the tidal force to object separation, the time-dependence of the tidal forcing changes from sinusoidal to one strongly peaked at pericentre, and a broad frequency spectrum results.

**Linear theory** If  $\epsilon$  (Equation 10.66) is small, the tidal response can be determined using linear theory, and the tidal disturbance treated as a small perturbation of a steady, axisymmetric state. For each component of the tidal potential there is an independent linearly-related response, described by a response function.

Specifically (Ogilvie, 2014), if a tidal potential component  $\text{Re}[\mathcal{A}(r/R)^l Y_l^m(\theta, \phi) e^{-i\omega t}]$  is applied to a body of nominal radius  $R$ , and the resulting deformation generates an external gravitational potential perturbation  $\text{Re}[\mathcal{B}(R/r)^{l+1} Y_l^m(\theta, \phi) e^{-i\omega t}]$ , then the complex dimensionless ratio  $k_l^m(\omega) = \mathcal{B}/\mathcal{A}$  defines the (potential) Love number (cf. box, page 533). The imaginary part,  $\text{Im}[k_l^m(\omega)]$ , quantifies the part of the response that is out of phase with the tidal forcing, and which is associated with transfer of energy and angular momentum.

The torque, power and dissipation rate are all quantities of second order in  $\epsilon$ , which can be calculated within a linear analysis, and which are proportional to the imaginary part of the response function. The dissipation rate depends on whether the body rotates (non-)uniformly.

Because of energy dissipation, the quadrupole moment of body 1 is not instantaneously related to the tidal field, and is therefore not generally aligned with the radial direction. This effect is, again, often modeled (imperfectly) by allowing for a certain time lag in the response. The dissipative part of the net force between the bodies means that the radial force is retarded (and therefore resists the oscillatory radial motion associated with any orbital eccentricity), and that an angular force arises that resists the relative angular motion associated with any inequality of the spin and orbital angular velocity vectors. This force also gives rise to a tidal torque that couples the spin and orbit, allowing an exchange of angular momentum. Both forces are resistive in nature and are accompanied by energy dissipation.

**Modified tidal quality factor,  $Q'$**  It is then common to write (Ogilvie, 2014, section 2.2)  $|\text{Im}[k_l^m(\omega)]|$  as  $k_l/Q$ , where  $Q$  is the *tidal quality factor*. Furthermore, for a homogeneous body,  $k_l/Q$  is frequently written as  $k_l^{\text{hom}}/Q'$  where  $Q'$  is the *modified tidal quality factor*. This has the advantage of combining  $Q$  with  $k_l$ , which may not be known accurately as it depends on the interior structure, whereas  $k_l^{\text{hom}}$  has a simple analytical expression. Again, the *phase lag* in the tidal response is  $1/Q$ .

The concepts of quality factor and phase lag are based on simplified models in which the tidal response resembles the hydrostatic form, slightly retarded in phase but unaffected in amplitude. Neither is  $Q$  a fundamental material property, but rather a dimensionless parameterisation of a response function; as well as depending on  $l$ ,  $m$  and  $\omega$ ,  $\text{Im}[k_l^m(\omega)]$  depends on the body’s internal structure and angular velocity (Goldreich, 1963; Ogilvie, 2014).

The fundamental assumptions (and shortcomings) of this *constant angular lag model*, in particular in the region of spin–orbit resonance, have been detailed and emphasised (Williams & Efroimsky, 2012; Efroimsky & Makarov, 2013; Makarov & Efroimsky, 2013).

For the solar system giants,  $0.1 < k_2 < 0.4$  (Gavrilov & Zharkov, 1977; Kramm et al., 2012). For the Sun,  $k_2 \approx 0.0351$ .

**Rate and direction of tidal evolution** For small values of (and lowest order in)  $e$  and  $i$ , Equations 6–9 of Ogilvie (2014) give the rates of change of  $a$ ,  $e$ , the spin angular velocity of body 1, and the obliquity of body 1 due to tidal dissipation in body 1, where spin and orbit components of angular velocity ( $\Omega$ ) and angular momentum

( $L$ ) are designated by subscripts 's' and 'o'. For example,

$$\frac{1}{a} \frac{da}{dt} = -3\kappa_{2,2,2} \frac{M_2}{M_1} \left( \frac{R_1}{a} \right)^5 \Omega_o, \quad (10.69)$$

where  $\kappa_{l,m,n} = \text{Im}[k_l^m(n\Omega_o)]$ . For  $|\kappa| \lesssim 1$ , it follows that (i) for  $\epsilon \ll 1$ , tidal evolution occurs on a time scale much longer than the orbital time scale; (ii) tidal dissipation in the two bodies may be of comparable importance, such that dissipation in the smaller body can dominate the evolution of  $e$ , and also of  $a$  before body 2 becomes synchronised; and (iii) for  $L_s \ll L_o$ , spin evolution proceeds much more rapidly than orbital evolution.

Competing contributions to  $\dot{e}$  and  $\dot{i}$  mean that various possibilities arise for the signs of the rates of change of these quantities (Jeffreys, 1961; Goldreich, 1963; Goldreich & Soter, 1966; Kaula, 1968). Combinations are tabulated by Ogilvie (2014, figure 4).

In the (unlikely) event that all components have the same time lag  $\tau$  (e.g. Darwin, 1880; Alexander, 1973; Hut, 1981), results simplify to (Ogilvie, 2014, equations 12–15)

$$\frac{1}{a} \frac{da}{dt} = -6k_2\tau(\Omega_o - \Omega_s) \frac{M_2}{M_1} \left( \frac{R_1}{a} \right)^5 \Omega_o, \quad (10.70)$$

$$\frac{1}{\Omega_s} \frac{d\Omega_s}{dt} = 3k_2\tau(\Omega_o - \Omega_s) \frac{L_o}{L_s} \frac{M_2}{M_1} \left( \frac{R_1}{a} \right)^5 \Omega_o, \quad (10.71)$$

$$\frac{1}{e} \frac{de}{dt} = -\frac{3}{2} k_2\tau(18\Omega_o - 11\Omega_s) \frac{M_2}{M_1} \left( \frac{R_1}{a} \right)^5 \Omega_o, \quad (10.72)$$

$$\frac{1}{i} \frac{di}{dt} = -\frac{3}{2} k_2\tau \left[ \Omega_s + (2\Omega_o - \Omega_s) \frac{L_o}{L_s} \right] \frac{M_2}{M_1} \left( \frac{R_1}{a} \right)^5 \Omega_o. \quad (10.73)$$

It follows that  $e$  is excited for  $\Omega_s/\Omega_o > 18/11$ , and  $i$  is excited for  $\Omega_s/\Omega_o > 2L_o/(L_o - L_s)$  if  $0 < L_s < L_o$ , or always if  $L_s < 0$  (i.e.  $\Omega_s < 0$ ).

Other work has investigated the dependency of  $Q$  on frequency, for both solar system objects and giant exoplanets, and under alternative assumptions about the body's response (Hubbard, 1974; Goldreich & Nicholson, 1977; Hut, 1981; Rasio et al., 1996; Eggleton et al., 1998; Terquem et al., 1998; Ivanov & Papaloizou, 2004b; Ogilvie & Lin, 2004; Wu, 2005; Ogilvie & Lin, 2007; Ferraz-Mello et al., 2008; Jackson et al., 2008b; Goodman & Lackner, 2009; Greenberg, 2009).

More complex tidal models, including for arbitrary  $e$  and  $i$ , have also been formulated (Alexander, 1973; Zahn, 1977; Hut, 1981; Neron de Surgy & Laskar, 1997; Eggleton et al., 1998; Lin et al., 2000; Mardling & Lin, 2002; Ivanov & Papaloizou, 2004b,a; Ogilvie & Lin, 2004; Efroimsky & Lainey, 2007; Ivanov & Papaloizou, 2007; Wisdom, 2008; Leconte et al., 2010a; Matsumura et al., 2010a; Ivanov & Papaloizou, 2011).

Qualitatively, the tidal torque seeks to equalise the spin and orbital angular velocity vectors through an exchange of angular momentum and the dissipation of energy. If  $L_s \ll L_o$ , tidal dissipation tends to equalise the spin and orbital angular velocity

vectors, involving only a small change in the orbit. For a circular orbit, this means both synchronisation of the spin with the orbit and alignment of the spin axis with the orbit normal, with the final angular velocity vector determined by the total angular momentum. For an eccentric orbit, the orbital angular velocity is not constant, and there is a tendency towards 'pseudo-synchronisation', i.e. spin at a rate close to, but slightly less than, the instantaneous orbital angular velocity at the pericentre, where the tidal interaction is strongest (Peale & Gold, 1965; Hut, 1981; Makarov & Efroimsky, 2013).

Both radial force and tidal torque contribute to the evolution of eccentricity, which can (along with the obliquity) either increase or decrease as a result. Circularisation and spin-orbit alignment may be regarded as the normal outcomes of tidal dissipation; in order to increase  $e$  or  $i$ , the energy source associated with an asynchronous spin is needed.

**Time scales** Theoretical time scales for tidal evolution have been estimated for binary star systems (e.g. Zahn, 1977; Hut, 1981) and for a number of exoplanet systems (e.g. Rasio & Ford, 1996; Mardling & Lin, 2002; Dobbs-Dixon et al., 2004; Adams & Laughlin, 2006a). Evolutionary time scales, on which the orbits *circularise*, are typically of order 1 Gyr (Hut, 1981; Ferraz-Mello et al., 2008).

In contrast, tides raised by the star on hot Jupiters should drive them into synchronous *rotation* much more rapidly (Goldreich & Peale, 1966; Peale, 1977; Guillot et al., 1996; Rasio et al., 1996; Lubow et al., 1997; Marcy et al., 1997; Murray & Dermott, 2000). This can be seen from the time scale for tidal despin (Goldreich & Soter, 1966; Hubbard, 1984)

$$\tau_{\text{syn}} \approx Q \left( \frac{R_p^3}{GM} \right) \left( \frac{M_p}{M_\star} \right)^2 \left( \frac{a}{R_p} \right)^6 (\omega - \omega_s), \quad (10.74)$$

where  $Q$ ,  $a$ ,  $\omega$  and  $\omega_s$  are the planet's tidal dissipation factor, orbital semi-major axis, rotational angular velocity, and synchronous (orbital) angular velocity.

Numerical estimates for HD 209458 b (with  $\omega = \omega_J$ ) suggest a spin down  $\tau_{\text{syn}} \sim 3Q$  yr. Assuming  $Q \sim 10^5$  (Lubow et al., 1997), HD 209458 b should then be drawn into synchronous rotation with its 3.5-d orbital period within a few Myr, much shorter than the circularisation time scale. Spin down for some hot Jupiters are perhaps measurable in years to decades (e.g. Léger et al., 2009).

During spin down of the planet, angular momentum conservation requires that the orbit expands, while the total energy dissipated (estimated as  $\sim 4 \times 10^{34}$  J for HD 209458) resulting in a 'thermal pulse' which has been considered, and along with tidal circularisation largely dismissed, as an ingredient in discussions of the inflated radii of hot Jupiters (Showman & Guillot, 2002).

**Infall time** Levrard et al. (2009, equation 5) gives an expression for the time remaining for the planet to infall and merge with its host star from its initial orbital distance  $a$  (at small  $e$ , with  $n \equiv 2\pi/P$ ) as

$$\tau_a \approx \frac{1}{48} \frac{Q'_\star}{n} \left( \frac{a}{R_\star} \right)^5 \left( \frac{M_\star}{M_p} \right), \quad (10.75)$$

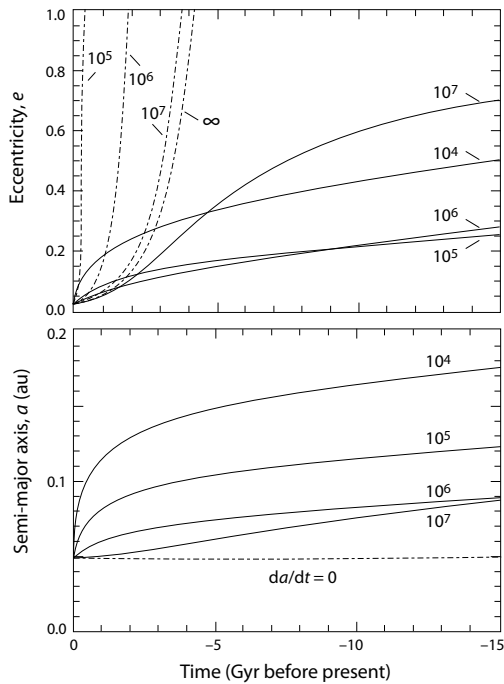


Figure 10.40: Tidal evolution of  $e$  and  $a$  for  $\tau$  Boo b. Orbits are traced backwards in time from their current values ( $e = 0.023$ ,  $a = 0.0595$  au).  $Q_p$  is fixed at  $10^5$ , and results are shown for various assumed values of  $Q_*$ . Solid lines correspond to numerical integration of equations of the form 10.70 and 10.72. Dashed lines show the very different exponential solutions if  $a$  is (inappropriately) assumed to be constant. From Jackson et al. (2008b, Figure 3), by permission of IOP Publishing/AAS.

which depends only on the tidal dissipation within the star, not within the planet.

For planets delivered to very short orbits, Chernov (2017) has estimated that a  $1M_J$  planet orbiting a  $1M_\odot$  star will fall onto the star within its main-sequence lifetime for  $P_{\text{orb}} \sim 2.8$  d, and similarly onto a  $1.5 - 2M_\odot$  star within its main-sequence lifetime for  $P_{\text{orb}} \sim 2$  d.

Observational evidence for tidally-disrupted planets is described in Section 6.14.21. In the process, gas giant envelopes may be tidally stripped to reveal their dense protoplanetary cores (e.g. Liu et al., 2013d).

**Constraints on tidal dissipation** In the solar system, values of  $Q$  separate into two distinct groups: for the terrestrial planets and satellites of the major planets  $Q = 10 - 500$ , while for the major planets  $Q > 6 \times 10^4$  (Goldreich & Soter, 1966). Values of  $Q_p$  for giant exoplanet are currently highly uncertain, and have tended to rely either on estimates derived from models of the tidal evolution of the Galilean satellites (e.g. Yoder & Peale, 1981; Greenberg, 1982, 1989; Aksnes & Franklin, 2001), or on models of internal dissipation (e.g. Goldreich & Nicholson, 1977; Ogilvie & Lin, 2004).

Thus, values of  $Q_p = 10^6$  for giant exoplanets and

$Q_* = 10^5$  for host stars were adopted in some early studies of tidal evolution, while for terrestrial exoplanets (or for rocky cores),  $Q_p = 100$  may be more appropriate (Goldreich & Soter, 1966; Lambeck, 1977; Dickey et al., 1994; Mardling & Lin, 2002; Barnes et al., 2008c; Efroimsky, 2012b,a; Efroimsky & Makarov, 2014; Auclair-Desrotour et al., 2014).

As for binary stars, the clearest evidence for star-planet tidal interactions comes from the joint distribution of orbital eccentricity and orbital period (although some further circumstantial evidence for tidal transfer is inferred from the rapid spin rate of certain host stars, §10.11.8). Orbits of shorter period are more likely to be of low eccentricity (e.g. Kipping, 2013b). This can be explained by tidal circularisation due to dissipation in the planet, and is broadly consistent with  $Q'_p \approx 10^{6.5}$  (Jackson et al., 2008b, 2009; Schlaufman et al., 2010; Husnoo et al., 2012). In systems with more massive planets, such as CoRoT-3 (Husnoo et al., 2012), dissipation in the star may also influence circularisation.

Further uncertainty on  $Q_p$  follows from the existence of close-in planets with non-zero eccentricity (Matsumura et al., 2008), although these may be excited by an outer companion (§10.11.10).

Jackson et al. (2008b) examined the hypothesis that tides are responsible for damping eccentricities by numerically integrating simplified equations of the form 10.70 and 10.72 for exoplanets closer than 0.2 au. Integrations began at the current  $a$  and  $e$ , and proceeded back to the time where tidal evolution began to dominate the orbital evolution, i.e. around the epoch that the protoplanetary disk was cleared, and collisional effects diminished. Both tides raised on the planet and on the star are included. It is further assumed that, although initially unknown, the same value of  $Q_p$  applies to all planets, and the same  $Q_*$  to all stars.

For each pair of assumed  $Q_p$  and  $Q_*$ , integration yields a distribution of initial eccentricities. A comparison between these computed distributions, and the observed distributions of  $e$  for planets with larger  $a$ , leads to their best-estimate of  $Q_p = 10^{6.5}$  and  $Q_* = 10^{5.5}$ . Still larger values of  $Q_p > 10^7$  have been inferred for some hot Jupiters, for example OGLE-TR-56 b (Carone & Pätzold, 2007), and CoRoT-7 b (Léger et al., 2009).

Shorter period planets such as Kepler-78 b (Sanchis-Ojeda et al., 2013a), and the unconfirmed  $P = 4.2$  h KOI-1843.03 orbiting Kepler-974 (Rappaport et al., 2013) actually provide weaker constraints on  $Q_*$  because of their lower  $M_p$  and higher  $\rho_*$ .

For  $\tau$  Boo b, Figure 10.40 illustrates the dependence of  $\dot{e}$  and  $\dot{a}$  on  $Q_*$  for an assumed  $Q_p = 10^5$ . Incorporating tidal effects on both bodies leads to a complex relation between  $\dot{e}$  and  $Q_*$ , as  $Q_*$  increases from  $10^4$  to  $10^7$ .

Hansen (2010) analysed an ensemble of observations within the equilibrium tide theory of Eggleton et al.

(1998, see §10.11.6), including effects of tidal heating and tidal evolution of the spin and orbit. He assumed a single bulk dissipation constant per unit mass,  $\sigma_*$ , for all host stars in the range  $0.7 - 1.4M_\odot$ , and a second similar parameter,  $\sigma_p$ , for all gas giants  $M_p > 0.3M_J$ , with a common time lag  $\tau$ , and with

$$\sigma = \frac{2}{3} k_2 \tau \frac{G}{R^5} = \frac{1}{Q' |\dot{\omega}|} \frac{G}{R^5}. \quad (10.76)$$

Hansen (2010) found that the value of  $\sigma_*$  corresponding to  $Q'_* = 10^6$  in the case of the present Sun for a tidal period of 6 d, would result in tidal evolution too rapid by some two orders of magnitude. His preferred value of  $\sigma_p$  corresponds to  $Q'_p = 10^8$  in the case of Jupiter for a tidal period of 4 d, or to  $10^7 \lesssim Q'_p \lesssim 10^8$  for the circularisation of hot Jupiters. The two parameters provided a coherent description of a wide range of observed systems.

For stars with spin periods much longer than the planet's orbital period, theoretical estimates of dissipation efficiencies by Penev & Sasselov (2011) yielded  $Q_* = 10^8 - 3 \times 10^9$ , and resulting in orbit lifetimes much longer than the ages of the observed systems. Further studies suggest that the population of known planets is inconsistent with  $Q_* < 10^7$  (Penev et al., 2012).

Hansen (2012) calculated the value of  $\sigma$  for each star or planet using equilibrium tidal theory, and including an empirical correction factor  $\nu_0$  for the turbulent viscosity. He found that a modest correction  $\nu_0 \approx 1.5$  is sufficient to explain the circularisation of binaries containing a giant star (Verbunt & Phinney, 1995), while also being compatible with the non-zero eccentricities of several massive, short-period exoplanets.

It is useful to recall that  $Q'$  is not a fundamental property of a body. Even in linear tidal theory it is expected to depend on the tidal frequency, and on the integers  $l$  and  $m$  of the different spherical harmonics. Although theory does not yet explain why  $Q'_* \approx 10^6$  for the circularisation of solar-type binaries, it can plausibly explain why  $Q'_*$  should be much larger for the orbital decay of hot Jupiters: the host stars are mostly spinning more slowly than in close binaries, and the tidal frequency of the asynchronous tide in the fluid frame is usually such that  $|\dot{\omega}| \gg \Omega_s$ . But the eccentricity tides in a synchronised binary star have  $|\dot{\omega}| = \Omega_s$  and can excite inertial waves in the convective zone, producing a stronger tidal response (Ogilvie & Lin, 2007; Ogilvie, 2014).

In practice, tidal dissipation in rotating low-mass stars is dependent on the structural and rotational evolution of the star, and its metallicity, with models indicating variation over several orders of magnitude between the pre-main sequence and the tip of the red-giant branch (Gallet et al., 2017a; Bolmont et al., 2017a).

**Ongoing inward migration** Direct evidence for ongoing inward migration is less clear than for circularisation. The existence of numerous planets with  $P \lesssim 1$  d im-

plies that  $Q'_*$  must greatly exceed the empirical estimate of  $10^6$  deduced from the circularisation of solar-type binary stars; otherwise the remaining lifetimes of the very short-period planets would be implausibly short.

An extreme example is WASP-18 b (Hellier et al., 2009a), whose remaining lifetime would be  $\sim 10^6$  yr for  $Q'_* = 10^6$ ; in this case orbital decay should be detectable within a few years through transit time variations (Hellier et al., 2009a). Watson & Marsh (2010) suggested that the effect might be masked by orbital period changes resulting from a variation of the quadrupole moment of the star during its magnetic activity cycle.

For OGLE-TR-56 b, Adams et al. (2011a) constrained  $\dot{P} = -2.9 \pm 17$  ms yr $^{-1}$ , i.e. consistent with zero.

Schlaufman & Winn (2013) found evidence for planet destruction by inward migration due to tidal dissipation in subgiants. The paucity of planets with  $P \lesssim 200$  d around subgiants, in comparison with their presumed main-sequence progenitor stars, is taken as evidence that the shorter-period planets were consumed as the star swelled and developed a deep convective envelope after leaving the main sequence.

**Application to known exoplanet orbits** Applying the resulting tidal models with the derived values of  $Q_p$  and  $Q_*$  to known close-in systems, Jackson et al. (2008b) demonstrated that, in several cases, stellar and planetary tides have significantly reduced their semi-major axes after the planets formed and gas migration ceased, leading to a subsequent reduction of a factor two or so in their semi-major axes since formation (Figure 10.41). While tidal evolution for many planets is evidently slower than in the past, some, such as HD 41004B b, are still undergoing rapid changes in  $a$  and  $e$ .

Reliable estimates of a circularisation time scale require the coupled treatment of the evolution of  $a$  and  $e$ . Much shorter circularisation time scales are inferred if the concurrent changes in  $a$  are ignored, as evident from the dashed curves in Figure 10.40a. Such rapid tidal circularisation time scales estimated for HD 209458 b have led to other mechanisms for maintaining the planet's eccentricity being proposed (such as an additional planet by Mardling, 2007), and to tidal heating being excluded as an explanation for its anomalously large radius. In contrast, the coupled equations suggests that  $e$  can remain fairly large, with significant tidal heating operating over the past billion years (Jackson et al., 2008b,c).

**Distinguishing rocky from gaseous planets** Models predict that rocky planets can grow large enough to become gas giants when they reach  $5 - 10M_\oplus$ , but the precise transitional mass is unknown. Tidal models predict that the orbits of rocky planets are circularised much more rapidly than gaseous bodies, suggesting that the former will tend to be found on circular orbits at larger semi-major axes than the latter. Well-sampled transits

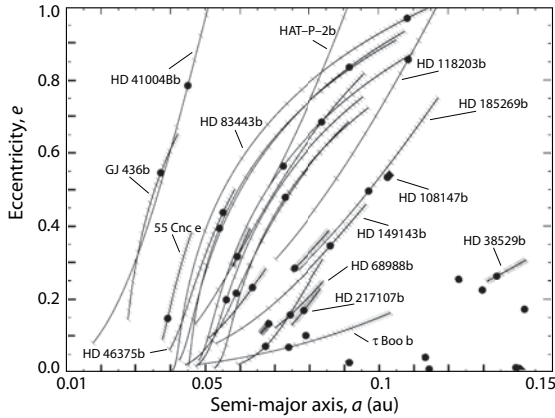


Figure 10.41: Tidal evolution of  $e$  and  $a$  for the sample of known close-in extrasolar planets using best-fit values of  $Q_p = 10^{6.5}$  and  $Q_* = 10^{5.5}$  obtained from a match between predicted initial eccentricities, and the distribution of eccentricities of more distant orbiting planets. Solid curves represent the trajectories of orbital evolution from current orbits (lower left end of each curve) backward in time (toward the upper right). Tick marks are spaced every 500 Myr to indicate the rate of tidal evolution. Tidal integrations were performed for 15 Gyr for all planets, but the filled circles indicate the initial values of orbital elements at the beginning of each planet's life. From Jackson et al. (2008b, Figure 7), by permission of IOP Publishing/AAS.

can provide a minimum orbit eccentricity (§6.13.6), allowing a measurement of this differential circularisation. Barnes (2015) showed that the effect should be present in the Kepler data, but that it is not evident, at least at the individual planet level. Neither is there evidence of tidal circularisation at any planetary radius, probably because the available data are not accurate enough.

The effect probably is evident in the Kepler data for eclipsing binary stars, where tidal circularisation is predicted to be faster for relatively cool stars with convective outer layers, compared to hotter stars with radiative outer layers (Van Eylen et al., 2016c).

#### 10.11.4 Tidal equilibrium and Darwin stability

The preceding discussions aim to characterise ongoing tidal effects. A classic problem in dynamics is to determine the endpoint of tidal evolution, that is the tidal equilibrium states for self-gravitating systems that include both rotational and orbital motion (Darwin, 1879a, 1880), which may still lie some Gyr in the future.

For a two-body system that conserves total angular momentum, tidal evolution leads either to a stable equilibrium state, or to orbital decay all the way to the Roche radius and tidal destruction. In the former *tidal equilibrium*, or *Darwin-stable state*, the planet remains in a stable orbit, never inspiraling onto the star, while the star has been spun-up to the point of synchronisation of the orbit, planetary, and stellar spin periods.

In most binary stars, the theoretical endpoint of tidal evolution (in the absence of magnetic braking, gravitational radiation and stellar evolution) is such a tidal equilibrium, or *double synchronous state*, in which the two bodies have a circular orbit with aligned and synchronised spins (as in the Pluto–Charon system; Tholen et al. 1987). In the absence of effects such as differential rotation arising from convection or meridional circulation, there is then only a static tidal deformation, with no further dissipation, and no further tidal evolution.

In extreme mass ratio systems, however, including many short-period exoplanets, this equilibrium cannot be reached, suggesting that the majority are destined to spiral in to their host star to be destroyed by tides.

The existence of an equilibrium state (which does not depend directly on the energy dissipation mechanisms that allow systems to attain such states) depends on the relationship between the total angular momentum,  $L_{\text{tot}}$ , being the sum of the spin and orbital contributions,  $L_{\text{tot}} = L_s(\Omega) + L_o(\Omega)$ . These components are increasing and decreasing functions of  $\Omega$ .  $L_{\text{tot}}$  therefore has a minimum, critical value  $L_{\text{crit}}$  at  $\Omega = \Omega_{\text{crit}}$ , with (Counselman, 1973; Hut, 1980; Levrard et al., 2009)

$$L_{\text{crit}} = 4 \left[ \frac{G^2 M_*^3 M_p^3}{27 M_* + M_p} (C_p + C_*) \right]^{1/4}, \quad (10.77)$$

where  $M_p$ ,  $C_p$  and  $M_*$ ,  $C_*$  are the masses and polar moments of inertia of the planet and star respectively. Alternatively (Ogilvie, 2014, eqn 1)

$$L_{\text{crit}} = 4I\Omega_{\text{crit}} \quad (10.78)$$

$$\Omega_{\text{crit}} = (GM)^{1/2} \left( \frac{\mu}{3I} \right)^{3/4}, \quad (10.79)$$

where  $M = M_1 + M_2$  is the total mass,  $\mu = M_1 M_2 / M$  is the reduced mass, and  $I = I_1 + I_2$  is the sum of the spin moments of inertia (assumed constant).

If  $L_{\text{tot}} < L_{\text{crit}}$ , no equilibrium state exists and the system ultimately merges. If  $L_{\text{tot}} > L_{\text{crit}}$ , two equilibrium states exist that are characterised by the relation between the equatorial and orbital planes, circularity of the orbit, and synchronisation between rotational and orbital periods when no further dissipation occurs (Counselman, 1973; Hut, 1980).

The outermost state with  $\Omega < \Omega_{\text{crit}}$  has  $L_o > 3L_s$  and is stable. The more compact one with  $\Omega > \Omega_{\text{crit}}$  has  $L_o < 3L_s$  and is unstable; it may in any case be inaccessible if the orbit would be too small relative to the sizes of the bodies. Hut (1980) further demonstrated that a binary system can be in tidal equilibrium only if co-planarity, circularity and corotation have been established.

Figure 10.42 shows the evolutionary paths for a planet interacting tidally with a star in the circular, aligned case ( $e = i = 0$ ) in the absence of magnetic braking and other influences. If  $L_{\text{tot}} < L_{\text{crit}}$ , then the orbit

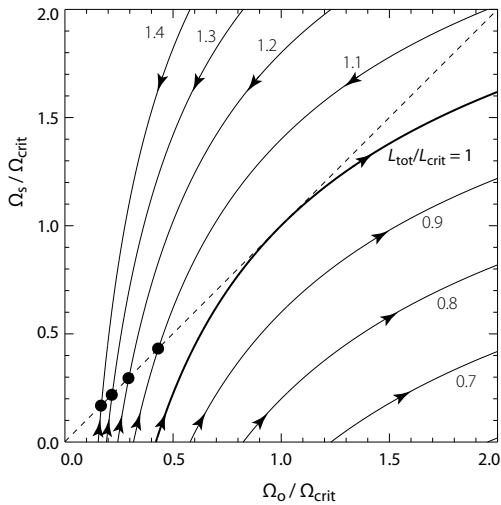


Figure 10.42: Evolutionary paths for a planet interacting tidally with a star in the circular, aligned case ( $e = i = 0$ ). Axes represent the (stellar) spin and orbital angular velocities in units of the critical value (Equation 10.79). Contours show the total angular momentum  $L_{\text{tot}}$ , with the direction of evolution corresponding to energy dissipation. The planetary spin is assumed unimportant. On the dashed line, stellar spin and orbit are synchronised. Circles represent stable tidal equilibria when  $L_{\text{tot}} > L_{\text{crit}}$  (Equation 10.79). Systems with  $L_{\text{tot}} < L_{\text{crit}}$  evolve towards planetary destruction. The equation of each contour is  $(\Omega_s / \Omega_{\text{crit}}) + 3(\Omega_o / \Omega_{\text{crit}})^{-1/3} = 4(L_{\text{tot}} / L_{\text{crit}})$ . From Ogilvie (2014, Figure 10), reprinted with permission from AAS.

decays and the star is spun up; if  $L_{\text{tot}} > L_{\text{crit}}$  then a stable tidal equilibrium may be approached. All satellite systems of solar system planets have  $L_{\text{tot}} > L_{\text{crit}}$ . For the giant planets,  $L_{\text{tot}} \gg L_{\text{crit}}$  and  $L_o \ll 3L_s$ .

Adams & Bloch (2016) summarised this as follows. For 2-body systems, three evolutionary paths are available: (a) the orbit of the secondary can decay inward and eventually collide with the primary, where the orbital angular momentum is transferred to the rotation of the primary; (b) the orbit can gain angular momentum from the primary and move outwards toward an unbound state; (c) the system can approach a stable tidal equilibrium configuration, where the orbit and spins of both bodies have the same period and their angular momentum vectors point in the same direction. In order for the equilibrium state to exist, the system must have a minimum amount of total angular momentum; in order for the system to reside in the equilibrium state, its orbital angular momentum must be at least three times larger than the spin angular momentum.

Adams & Bloch (2015) generalised the stability calculation to include the quadrupole moment of the host star, finding that most of the (Kepler) systems in their sample have enough total angular momentum, but insufficient orbital angular momentum, to exist in an equilibrium configuration.

**Observed systems** In considering the stability of observed systems, two points are worth recalling. First, since tidal evolution occurs over such long time scales, often comparable to the age of the Universe, many extant systems are not expected to have reached their low-

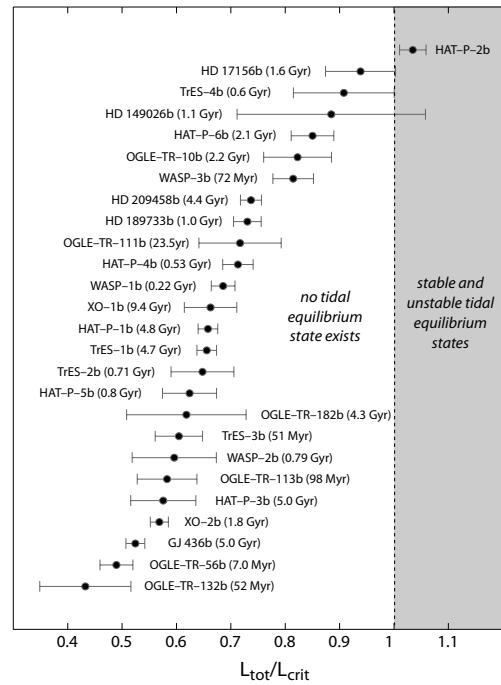


Figure 10.43: Transiting planets by increasing values of the ratio between the total angular momentum of the system,  $L_{\text{tot}}$ , and the critical angular momentum,  $L_{\text{crit}}$ . The time remaining for each planet to collide with its host star is indicated in brackets, assuming  $Q'_* = Q'_p = 10^6$ . Although presently tidally-unstable, HAT-P-2 will asymptotically evolve inwards from its present orbital distance ( $\sim 0.068$  au) towards the (outermost, stable) equilibrium value  $a_1 \approx a_{\text{crit}} \sim 0.048$  au. From Levrard et al. (2009, Figure 1), by permission of IOP Publishing/AAS.

est energy states. Second, tidal equilibrium is determined under the assumption of conservation of angular momentum, which must exceed a minimum value for the equilibrium state to exist. Although planetary systems can lose angular momentum, for example via stellar winds, systems that start with too little angular momentum generally have no means of gaining more.

For close-in exoplanets, such an analysis was first carried out for 51 Peg b by Rasio et al. (1996). Levrard et al. (2009) analysed 26 transiting systems, finding only HAT-P-2 to be in a stable tidal equilibrium state based on its value of  $L_{\text{tot}} / L_{\text{crit}}$  (Figure 10.43). This implies the eventual collision of the majority with their host star, and suggests that their nearly circular orbits, and the alignment between the stellar spin axis and the planetary orbit, may not be due to tidal dissipation alone. Under these conditions circularisation and synchronisation time scales lose their conventional meaning, and detailed numerical simulations are required to establish a system's tidal evolution.

Matsumura et al. (2010a) extended this to some 60 transiting systems, finding only CoRoT-3, CoRoT-6, HD 80606, and WASP-7 (and possibly HAT-P-2 and

WASP-10) to be Darwin stable within the current observational uncertainties. Stability of CoRoT-20 b based on similar criteria was confirmed by Deleuil et al. (2012).

In two systems with  $L_{\text{tot}} > L_{\text{crit}}$ , CoRoT-3 b and  $\tau$  Boo b, the stellar spin appears approximately synchronised with the orbit (Husnoo et al., 2012) and these systems may already be in, or close to, a stable equilibrium.

In the case of  $\tau$  Boo b it is likely that  $L_{\text{tot}} > L_{\text{crit}}$  by only a narrow margin; the same is true of KELT-1 (Siverd et al., 2012) and CoRoT-15 (Bouchy et al., 2011b).

Some short-period systems with  $L_{\text{tot}} > L_{\text{crit}}$  could be evolving towards a stable equilibrium, although magnetic braking may eventually reduce  $L_{\text{tot}}$  below  $L_{\text{crit}}$  and destroy the equilibrium (e.g. Damiani & Lanza, 2015; Li & Winn, 2016). Many longer period systems with massive planets also have  $L_{\text{tot}} > L_{\text{crit}}$ , but are not expected to undergo significant tidal evolution. For CoRoT-33 b, the orbital period is within 3% of a 3:2 resonance with the host star rotation (Csizmadia et al., 2015).

**Related observations** The presumably different origins of close-in hot-Jupiter systems further complicates interpretation of the relationship between stellar rotation and orbital period.

For those systems considered to be in spin-orbit alignment, Figure 10.44 shows their orbital periods  $P_{\text{orb}}$  and stellar rotation periods  $P_{\text{rot}}$ . The dashed line indicates planet orbits synchronised with the spin period of their host star. Orbits below the line, in which the orbital period is longer than the host star spin period, are sometimes referred to as ‘super-synchronous’. For  $P_{\text{orb}} < 5$  d, for example, these include CoRoT-11 b, HAT-P-56 b, and KELT-7 b. For these aligned close-in systems, angular momentum exchange between the star and the planet is expected to progressively slow down the rotation of the star, and extend the orbital period of the planet (Zhou et al., 2016b).

Walkowicz & Basri (2013) found that Kepler systems with  $R_p > 6R_{\oplus}$  and  $P < 10$  d are preferentially found in synchronised states between the stellar spin and the planet orbit. Four found to be in super-synchronous states had  $P > 5$  d, the largest of which had  $R_p = 0.7R_J$ . Other considerations of the tidal evolution of low-mass close-orbiting Kepler planets, and their resulting semi-major axis distributions, are given by Dong et al. (2017d).

**Star-planet-moon systems** Similar analyses can be carried out for 3-body systems, of specific interest being the stability of a star-planet-exomoon. Adams & Bloch (2016) modeled tidal equilibrium stability for such a hierarchical 3-body system, in which the energy and angular momentum budgets include contributions from the stellar spin, planetary orbit and planetary spin, and satellite orbit and satellite spin. By determining the optimised energy state of the system, subject to constant angular momentum, their study indicates that (and in

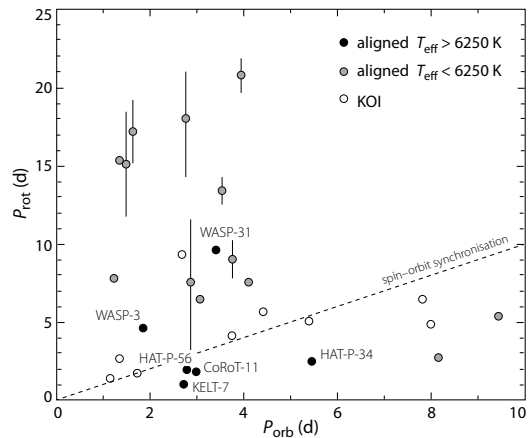


Figure 10.44: The orbital periods  $P_{\text{orb}}$  and stellar rotation periods  $P_{\text{rot}}$  of close-in hot-Jupiter systems in spin-orbit alignment ( $\lambda < 10^\circ$ ). The solid line marks 1:1 spin-orbit synchronisation. The rotation of Kepler candidates (KOI) were derived by Walkowicz & Basri (2013) from their light curves. Other spin rotation periods were inferred from the spectroscopic  $v \sin i$ , assuming  $i = 90^\circ$ , and so represent upper limits to the rotation periods. Of relevance for understanding spin-orbit misalignment, super-synchronous rotation for short period systems ( $P_{\text{orb}} < 5$  d) are only found in host stars of  $T_{\text{eff}} > 6250$  K. From Zhou et al. (2016b, Figure 4), © Oxford University Press.

contrast to the 2-body systems) star-planet-moon systems have no viable *long-term* tidal equilibrium state.

This conclusion is not in conflict with the presence of moons in the solar system: they will not survive indefinitely, but rather only over the Gyr that they evolve (Goldreich & Soter, 1966). Indeed, exomoons in other systems may have substantially shorter lifetimes (e.g. Barnes & O’Brien, 2002). Specifically, if exomoons exist, they do so only because the systems are not old enough for them to have dissipated their energy, or to have been scattered. Tidal forces, meanwhile, act to move a moon outward if the planetary rotation rate is larger than the orbital mean motion, and *vice versa*.

### 10.11.5 Synchronous and non-synchronous rotation

The spin rate of planets soon after their formation is believed to be much higher than their orbital mean motion (§12.4.5). One effect of tidal torques is that a close-in planet should have spun down to near synchronous rotation (in which the orbit and rotation periods coincide) over very short time intervals,  $\lesssim 1$  Myr, compared to the Gyr expected for orbit circularisation (§10.11.3). If the torque is of sufficient magnitude, and synchronisation is achieved, the orbiting planet is said to be *tidally locked*, as in the case of the Earth-Moon system. Most hot Jupiters are similarly expected to be tidally locked to their host stars, viz. with one hemisphere in permanent day and the other in permanent night. Direct knowledge of exoplanet spins is, meanwhile, only extremely limited.



For an axially symmetric planet in an *eccentric* orbit, Peale & Gold (1965) showed that spin rate does not relax to the orbital mean motion, but instead approaches a final value which is somewhat larger. Because the net tidal torque on the planet must average to zero over each orbit, and since the tidal torque  $\propto a^{-6}$  (Equation 10.74), the final spin rate will have a value lying between the angular velocity at pericentre and the mean motion, with its precise value determined by the frequency and amplitude dependence of the planet's  $Q$ . Referred to as a *pseudo-synchronous* orbit, the underlying assumptions (and inapplicability especially to Earth-like planets with rigid mantles), is critically examined by Makarov & Efroimsky (2013).

If the planet is not axially symmetric, Goldreich (1966a) showed that, if the tidal phase lag is independent of the tidal amplitude and frequency, then synchronous rotation will result when  $[3(B - A)/C]^{1/2} \geq \frac{1}{2}(9.5\pi e^2)$ , where  $A, B, C$  are its principal moments of inertia.

For reasonable values of these moments of inertia, Goldreich (1966a) also showed that many stable resonance spin states exist including, for example, for Mercury and the Moon. The problem is then to explain why some of these states are populated (specifically, synchronous rotation for the Moon, and the 3:2 state for Mercury) while others are not. The specific case of the Moon is discussed in Section 12.3.3.

Mercury makes three sidereal rotations for every two orbital revolutions around the Sun (box, page 678). This 3:2 spin-orbit resonance was discerned by radar observations (Pettengill & Dyce, 1965), and promptly explained by its large eccentricity ( $e = 0.21$ ) combined with its limited rigidity (Peale & Gold, 1965). Details of how it acquired this resonant state nevertheless remain under discussion. Considerations include chaotic evolution of its orbit (Correia & Laskar, 2004); effects of core-mantle friction (Correia, 2006; Correia & Laskar, 2009; Ferraz-Mello, 2015; Bartucelli et al., 2017); an evolution starting with retrograde and subsequent synchronous motion combined with impact events (Correia & Laskar, 2012; Wieczorek et al., 2012); and non-linear tides (Makarov, 2012).

An analysis for the case of triaxially-deformed rocky planets for rocky planets orbiting M dwarfs, and confirming the existence of asynchronous spin-orbit rotation states for sufficiently large deformations, is given by Zanazzi & Lai (2017c).

Further complexities arise in planets with dense atmospheres, core-mantle friction, or non-zero eccentricity and obliquity (e.g. Goldreich, 1966a; Goldreich & Peale, 1966; Greenberg & Weidenschilling, 1984; Winn & Holman, 2005; Dobrovolskis, 2007; Correia et al., 2008a; Rodríguez et al., 2008; Celletti & Chierchia, 2008; Rodríguez et al., 2012; Correia & Robutel, 2013; Cunha et al., 2015; Makarov et al., 2016).

### 10.11.6 Equilibrium tides and dynamical tides

Other physical effects can modify two-body tidal interactions. To provide a framework, Zahn (1977) distinguished two different types of tidal interaction.

*Equilibrium tides* occur when the normal oscillation modes of the tidally-disturbed object have much higher frequencies than the orbital frequency, conditions applicable to fully convective stars or planets. It is related to the classical theory of tides, viz. on the idea that the effect of dissipation is to cause the tidal response to lag behind the forcing with a constant time-lag (§10.11.3).

*Dynamical tides* occur when normal modes have oscillation frequencies comparable to the orbit frequency, such that their excitation cannot be neglected.

In another approach to tidal theory, Correia et al. (2014) compute the instantaneous deformations using a differential equation for the gravity field coefficients. The method allows large eccentricities, and is not limited to quasi-periodic perturbations.

**Equilibrium tides** For an idealised model of a homogeneous, incompressible, non-rotating, spherical fluid body with a viscosity proportional to pressure, the only oscillation mode that can be excited through periodic forcing by a single tidal component is the  $f$  mode of degree  $l > 1$  (Thomson, 1863; Sridhar & Tremaine, 1992).

For more complex fluid bodies, the *equilibrium tide* (distinct from tidal equilibrium) represents an approximation to the tidal response. It consists of a large-scale deformation, which in the case of a quadrupolar tide ( $l = 2$ ) is a spheroidal bulge. The density and pressure are distorted in order to achieve hydrostatic equilibrium in the instantaneous potential, which includes the distorted self-gravitational potential of the body in addition to the applied tidal potential.

Internal convection, and other forms of dissipation, are modeled as an effective (anomalous Navier-Stokes) viscosity (e.g. Zahn, 1966a,b, 1977; Goldreich & Nicholson, 1977; Goldreich & Keeley, 1977; Goldreich & Nicholson, 1989; Goodman & Oh, 1997; Eggleton et al., 1998; Eggleton & Kiseleva-Eggleton, 2001; Gu et al., 2003b; Ivanov & Papaloizou, 2004a; Penev et al., 2007, 2009b,a; Ogilvie & Lesur, 2012; Remus et al., 2012a).

As an example, the model of Eggleton et al. (1998) is based on equations governing the quadrupole tensor of a star distorted both by rotation and by the presence of a companion on a possibly eccentric orbit; a functional form for the dissipative force of tidal friction; and equations governing the rates of change of the magnitude and direction of stellar rotation, the orbital period and eccentricity. They provide a closed set of equations, valid for arbitrary obliquity, giving the effective lag time as a function of dissipation rate and quadrupole moment. Hansen (2010), for example, analysed the ensemble of exoplanet observations within this framework.

**Dynamical tides** More realistic models of stars and planets support other oscillation modes, which in turn introduce other possibilities for tidal forcing.

Oscillation modes of the Sun and other stars are characterised through helioseismology and asteroseismology (§8.6). Following Cowling (1941), modes are classified as *f* (fundamental, i.e. surface gravity waves), *p* (pressure, i.e. acoustic waves) and *g* (gravity, i.e. internal gravity waves). Natural frequencies of *f* and *p* modes ( $\gtrsim 10^{-4}$  Hz for the Sun) are generally too high to be excited directly by tidal forcing, because of the much lower spin and orbit frequencies. But *g* modes, which propagate in stably stratified (radiative) regions, and which are supported by buoyancy and Coriolis forces, form a dense spectrum at low frequencies, and may result in resonant excitation by tidal forcing.

The study of tidal forcing of low-frequency internal gravity waves in early-type stars, with their convective cores and radiative envelopes, was developed by Zahn (1970, 1975, 1977). Tidal dissipation occurs because of radiative damping near the stellar surface, which is more effective for lower tidal frequencies. *Dynamical tides* are expected to be more important than the equilibrium tide at higher frequencies (Savonije & Papaloizou, 1983, 1984; Goldreich & Nicholson, 1989; Goodman & Dickson, 1998; Terquem et al., 1998; Ivanov & Papaloizou, 2007; Goodman & Lackner, 2009; Papaloizou & Ivanov, 2010; Nagasawa & Ida, 2011; Fuller & Lai, 2012).

Modeling of dynamical tides in hot Jupiters, in which stellar irradiation makes the atmosphere stably stratified to depths of  $\sim 10^7$  Pa, has been developed by Lubow et al. (1997), and is described further by Ogilvie (2014).

### 10.11.7 Non-linear tides

Ogilvie (2014, Section 4) provides an introduction to non-linear tidal effects, in the context of both equilibrium and dynamical tides. Various phenomena may be relevant in understanding dissipation mechanisms, tidal quality factors, and associated time scales.

A hydrodynamic *elliptical instability* (or tidal instability) can arise in rotating flows with elliptical streamlines, and is suspected to be present in planets and stars which are elliptically deformed by tides (e.g. Cébron et al., 2010; Cébron et al., 2012; Cébron et al., 2013; Barker & Lithwick, 2013).

A non-linear coupling of tides and global (*f*, *p*, and *g*) oscillation modes, so far studied mainly in the context of close binary stars and neutron stars, may provide other possibilities for dissipation (Kumar & Goodman, 1996; Weinberg et al., 2012, 2013; Venumadhav et al., 2014).

Large tidal forcing amplitudes leads to other complex (non-linear) phenomena, and an additional amplitude dependence of the (modified) tidal quality factor. In the radiative zone of solar-type stars, for example, internal *wave breaking* of an asynchronous tide can pro-

duce rapid orbit decay if the planet and star are sufficiently massive, and if the star is sufficiently old (Barker & Ogilvie, 2010; Barker, 2011). Conversely, planets unable to cause wave breaking at the centre of their host (solar-type) stars may result in  $Q'_\star \gtrsim 10^7$ , and hence are likely to survive tidal decay (Barker & Ogilvie, 2011).

An important non-linear aspect of tidal interactions is the development of differential rotation through the non-uniform deposition of angular momentum by tidal disturbances, and the interaction of this differential rotation with the tides (Ogilvie, 2014).

Various studies continue to explore these and other effects (e.g. Guenel et al., 2014; Remus et al., 2015; Storch & Lai, 2015a; Barker et al., 2016; Barker, 2016a,b; Bolmont & Mathis, 2016; Frouard et al., 2016; Li & Winn, 2016; Mathis et al., 2016; Quillen et al., 2016).

### 10.11.8 Spin-up of host stars

In addition to evidence for tidal interactions provided by the distribution of orbit eccentricities as a function of semi-major axis, the host stars of several hot Jupiters are found to be spinning faster than expected (Pont, 2009; Husnoo et al., 2012), suggesting a tidal transfer of angular momentum from the orbit to the stellar rotation (Mardling & Lin, 2002; Bolmont et al., 2012).

Pont (2009) inferred an excess stellar rotation for a given spectral type, derived from radial velocity or photometry, for HD 189733, CoRoT-2, HAT-P-2 (HD 147506), and XO-3, with others also lying above the mean relation (HAT-P-1, WASP-4, WASP-5, and CoRoT-1). Tidal spin-up had previously been excluded for HD 189733 (Bouchy et al., 2005c) and CoRoT-2 (Alonso et al., 2008a).

Tidal spin-up has also been discussed for WASP-18 and WASP-19 (Brown et al., 2011a), and WASP-50 (Gillon et al., 2011b), for the OGLE transiting planets (Sasselov, 2003; Pätzold et al., 2004), and has been inferred for a number of non-transiting systems.

At least three stars,  $\tau$  Boo (Catala et al., 2007), CoRoT-3 (Husnoo et al., 2012), and HD 73256 (Shkolnik et al., 2005) show rotation compatible with synchronisation with the orbits of their hot Jupiters (as do KELT-1 and CoRoT-15 with their brown dwarf companions). These apparently synchronised systems probably have sufficient total angular momentum to attain a tidal equilibrium although, as F stars with shallow convection zones, the associated dissipation mechanism is unclear.

Planets orbiting brown dwarfs provide a particularly interesting case study for tidal evolution, partly because their planet-forming regions and habitable zone are extremely close-in, and partly because brown dwarfs spin up as they age, such that the co-rotation distance moves inward. Bolmont et al. (2011) found that planets formed at or beyond the corotation distance and with  $e \lesssim 0.1$  move outwards. Some planets initially interior to coro-

tation can survive if their inward tidal evolution is slower than the brown dwarf's spin evolution, but most initially close-in planets fall onto the brown dwarf. Some planets can survive in the habitable zone for Gyr, with  $P_{\text{orb}} \sim 10\text{h} - 10\text{d}$ , although in many cases the habitable zone moves inward past the planet's orbit in 10–100 Myr.

**Mass–period correlation** The corresponding angular momentum exchange implies that some planets must have spiraled towards their star by substantial amounts since dissipation of the protoplanetary disk. The initial planet orbital distance before tidal infall can be estimated by assigning the excess stellar rotation to the planetary orbit. Based on these arguments, Pont (2009) constructed a tidal mass–period diagram which partitions the mass–period plane according to the planet's sensitivity to tidal evolution (Figure 10.45). Below a certain separation corresponding to orbital periods of  $\sim 3\text{--}5\text{d}$ , the orbital properties ( $e$ ,  $a$ , and stellar rotation) are controlled by tidal effects, and can be very different from their initial values. He concluded that, in increasing order of mass, close-in planets would be expected to be tidally unaffected ( $M \ll M_J$ ), circularised ( $M \approx M_J$ ), spiraling in ( $M \approx 1 - 2M_J$ ), destroyed ( $M \approx 2 - 3M_J$ ), and synchronised ( $M \gtrsim 3M_J$ ).

Rapidly rotating main-sequence stars continue to be found hosting planets, some of the most rapid amongst them being 30 Ari B b (Guenther et al., 2009), OGLE2–TR–L9 (Snellen et al., 2009b), WASP–33 (Collier Cameron et al., 2010b), and CoRoT–11 (Gandolfi et al., 2010).

**Magnetic field effects** The time scales involved in tidal synchronisation may be too long for tidal interactions to be responsible for the observed excess in stellar angular momentum. Lanza (2010) proposed that part of the angular momentum excess may be due to star–planet magnetic interactions, leading to a reduction of magnetic breaking, and to a reduction in the angular momentum loss to the stellar wind (Weber & Davis, 1967).

The detailed magnetohydrodynamic model of Cohen et al. (2010) confirms that once the stellar and planetary Alfvén surfaces interact with each other, the stellar wind topology in the hemisphere facing the planet changes and the angular momentum loss to the wind decreases. Rather than the host stars being spun up, the effect amounts rather to a reduction in the stellar angular momentum lost.

Which of the two (tidal or magnetic) mechanisms dominates depends on the stellar type and the individual star–planet parameters.

**Radial velocity and transit surveys** The various effects of tidal evolution have implications for radial velocity and transit searches for very close-in planets.

Spin-up of the host star could result in a bias in radial velocity surveys, in which stars with rapid rotation may be dropped from consideration either due to their

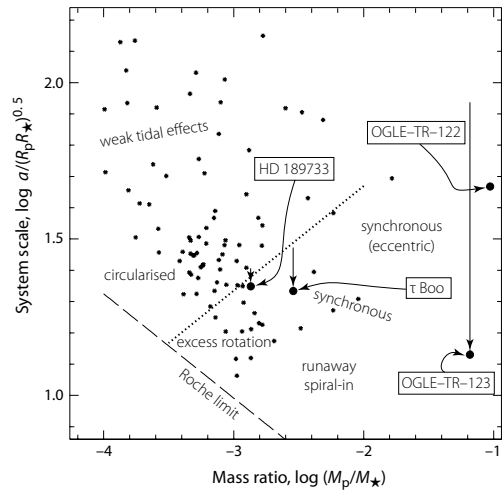


Figure 10.45: Tidal mass–period diagram for transiting planets. The system scale (ordinate) is given by the semi-major axis in joint units of  $R_\star$  and  $R_p$ . The dotted line marks the possible transition to detectable spin-up and orbit decay. Four objects are labeled, including the two transiting stars with the lowest masses (OGLE–TR–122 and OGLE–TR–123): arrows show the planet's original semi-major axis if the present excess angular momentum of the star is placed back in the planetary orbit. From Pont (2009, Figure 6), © Oxford University Press.

broadened spectral lines, or due to the expected correlation between rotation and photospheric activity.

The effect of tides on the radial velocity signatures of planet-hosting stars is considered in Section 2.5.3.

Rotation-induced stellar variability and short orbit periods may lead to transit curves qualitatively different from those assumed in standard searches (Figure 6.50), and a detection bias against massive close-in planets.

More generally, the probability of observing a transit increases for smaller  $a$ , but decreases as orbits become more circular (§6.13.6). These two aspects of tidal orbit evolution would imply that the probability of an observable transit has a dependence on the stellar age, which in turn would have implications for transit surveys, for example in young open clusters (§6.3.2).

### 10.11.9 Tidal heating

As the planetary orbit evolves through tidal coupling, orbital energy is converted into tidal energy, and substantial internal heating of the planet can result.

Since the orbital energy depends only on  $a$ , the term in  $\dot{a}$ , corresponding to the tides raised on the planet by the star (cf. Equation 10.70), also describes the planetary tidal heating rate. Jackson et al. (2008c) give

$$H = \frac{63}{4} \frac{(GM_\star)^{3/2} M_\star R_p^5}{Q_p'} a^{-15/2} e^2, \quad (10.80)$$

$$\approx 4 \times 10^{10} \text{ W} \left( \frac{M_\star}{M_\odot} \right)^{5/2} \left( \frac{R_p}{R_J} \right)^5 \left( \frac{Q_p'}{10^{6.5}} \right)^{-1} \left( \frac{a}{1 \text{ au}} \right)^{-15/2} e^2,$$

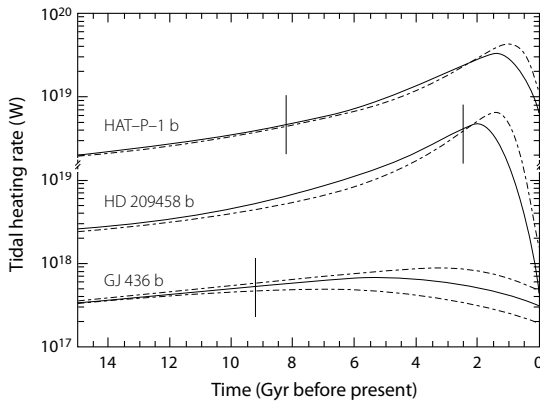


Figure 10.46: Tidal heating for HAT-P-1 b, HD 209458 b, and GJ 436 b as a function of time before present (the vertical scale is shifted for HAT-P-1 b). Vertical lines indicate estimated formation epochs. Solid curves are based on the planet's current nominal eccentricity. Dashed curves are the maximum and minimum heating consistent with uncertainty in the orbital elements. For HAT-P-1 b and HD 209458 b, observations cannot exclude zero eccentricity, so the lower bound on heating rates is formally zero, and only the upper limit is shown. From Jackson et al. (2008c, Figure 1), by permission of IOP Publishing/AAS.

where  $Q'_p = 3Q_p/2k$ , and  $k$  is the Love number.

Tidal heating increases as the planet moves inward toward its star, i.e. as  $a$  decreases, then decreases as its orbit circularises and  $e$  decreases. Plausible heating histories for planets with measured radii have been derived by Jackson et al. (2008c), using the same tidal parameters for the star and planet estimated above ( $Q_p = 10^{6.5}$ ,  $Q_\star = 10^{5.5}$ ). Examples are shown in Figure 10.46.

The same models show, for example, that GJ 876 d ( $0.02M_J$ ) is likely to have experienced substantial tidal heating. At its surface, the predicted tidal heating of  $10^{19} - 10^{20}$  W (assuming  $M_\star = 0.32M_\odot$ ,  $R_p = 0.143R_J$ ,  $a = 0.0208$  au,  $e = 0.01$ ,  $Q_p = 100$ , and  $k = 0.3$ ) compares with the  $7 \times 10^{17}$  W estimated to induce substantial melting of its mantle (Valencia et al., 2007a,c), such that it may not, in consequence, be a solid rocky planet.<sup>7</sup>

Other studies of tidal heating, and constraints on  $Q$ , have been variously reported (Matsumura et al., 2008; Selsis et al., 2013; Henning & Hurford, 2014), along with studies of specific (transiting) systems such as WASP-12 (Hebb et al., 2009), WASP-14 (Joshi et al., 2009), WASP-18 (Hellier et al., 2009a), CoRoT-7 (Léger et al., 2009), and Kepler-10 b, along with Mercury and Io (Makarov & Efroimsky, 2014).

The orbital energy dissipated to circularise a short-

period planet can significantly exceed the planet's internal binding energy, which suggests that rapid circularisation, if possible, either makes the planet very bright, or perhaps threatens to destroy it (Gu et al., 2003b). On Earth-like planets, tidally-induced thermal runaway can result from the coupling of tidal dissipation and mantle convection (Běhounková et al., 2011).

Tidal heating is similarly considered responsible for the volcanic activity of Jupiter's moon Io, and Saturn's moon Enceladus (§12.5.10). Effects on habitability (including on exomoons) are considered in Section 11.7.2.

**Inflated radii** Transit observations show a wide range of radii of hot Jupiters, not fully explained by conventional models (§6.28.4). In principle, tidal dissipation in the planet, due to the synchronisation of its spin and the circularisation of its orbit, can deposit a very large amount of energy, and the planet can be significantly heated and inflated if the deposition is sufficiently deep.

HD 209458 b and HAT-P-1 b are inferred to have undergone substantial tidal heating of up to  $3-4 \times 10^{19}$  W as recently as 1 Gyr ago, of the order estimated by Burrows et al. (2007a) to be necessary to explain their anomalously large radii. As an example of planets with radii more consistent with theoretical models, GJ 436 b has also been subject to much smaller tidal heating. However, the effect does not persist long after the orbit is circularised, and further studies have concluded that tidal heating cannot provide a general explanation of the radius anomalies (Leconte et al., 2010a; Hansen, 2010).

Arras & Socrates (2010), following earlier studies of Venus (Gold & Soter, 1969; Correia et al., 2003), have argued that a thermal tide, caused by asymmetric irradiation of the planet by the star, causes a torque that drives the planet away from synchronous spin. The competition between this torque and the gravitational tidal torque could result in a sustained asynchronous state with ongoing tidal dissipation.

### 10.11.10 Multi-planet systems

**Convergent migration with tidal circularisation** For multi-planet systems, the combined effects of disk-induced (convergent) migration with tidal circularisation was studied by Papaloizou (2011). He concluded that survival of, or degree of departure from, close commensurabilities in observed systems may indicate the effectiveness of tidal dissipation, which in turn may be related to the internal structure of the planets involved. Other studies illuminate many possibilities for more complex dynamical behaviour, including capture into Cassini states (§6.30.4), tidal Lidov-Kozai migration (§10.10.6), damping of mutual orbit inclinations, and excitation of eccentricities of inner planets (Correia et al., 2011; Rodríguez et al., 2011a; Correia et al., 2012; Laskar et al., 2012; Correia et al., 2013; Greenberg et al., 2013;

<sup>7</sup> For  $R_p = 10^4$  km, this leads to a surface heat flux  $\sim 10^4$  W m<sup>-2</sup>. For comparison, the heat flux of the most volcanically-active solar system body, Io of  $\sim 3$  W m<sup>-2</sup>, is dominated by tides (Peale et al., 1979; Yoder, 1979; Yoder & Peale, 1981; McEwen et al., 1992; Tyler et al., 2015), while that of the Earth,  $\sim 0.08$  W m<sup>-2</sup>, is dominated by radiogenic heat (Davies, 1999).

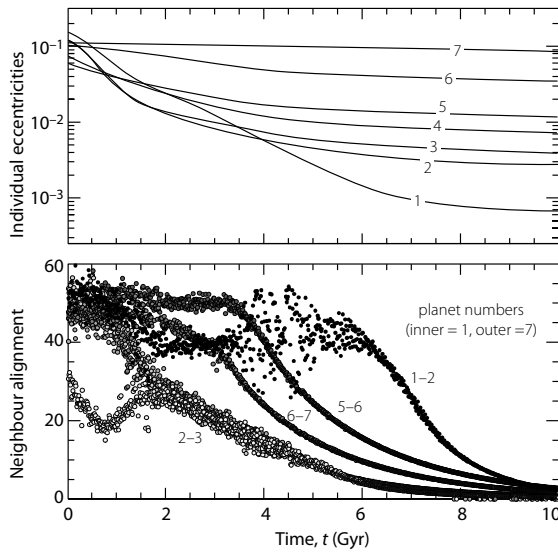


Figure 10.47: ‘Communal decay’ of a hypothetical 7-planet  $20M_{\oplus}$  system, with initial configuration ( $t = 0$ ) representing a packed Kepler system. The system evolves through secular gravitational interactions and tidal dissipation ( $Q'_{\oplus} \sim 10$ ). Top: individual eccentricities, which, at late times, increase monotonically with distance from the star. Bottom: evolution of the orbital alignment between neighbouring planets (points correspond to average offsets in longitude of pericentre, relative to the planet exterior to it, averaged over 0.01 Gyr). The innermost planet takes longest to align: even though most affected by tides, it is also strongly coupled to three other planets, with the coupling to planet 4 taking several Gyr to damp away. From Hansen & Murray (2015, Figure 7), © Oxford University Press.

Mathis & Remus, 2013; Rodríguez et al., 2013; Zhang et al., 2013a; Dong & Ji, 2014; Dong, 2014).

**Communal decay** In multi-planet systems, tidal effects can propagate outwards to much longer orbital periods. In what they (implicitly) refer to as *communal decay*, Hansen & Murray (2015) followed the orbit evolution of 50 realisations of a 7-rocky planet  $20M_{\oplus}$  compact system (detailed by Hansen & Murray, 2013, and chosen to resemble the statistical properties of observed Kepler planetary systems). They included the effects of tidal dissipation in all planets, assumed to have (Earth-like) tidal dissipation  $Q'_{\oplus} \sim 10$  (Goldreich & Soter, 1966). The evolution is driven by tidal dissipation in their interiors, but the system evolves as a whole due to secular gravitational interactions (Figure 10.47).

Consequences of this tidal coupling are that: (a) the continuous excitation of eccentricities due to secular perturbations sustains dissipation longer than for a single planet, and drives them inwards to even shorter period orbits; (b) orbits can be circularised out to  $P \sim 100$  d, some factor 10 larger than for single planets; (c) the innermost planet experiences, by far, the largest inward migration; (d) the resulting eccentricity distribution is

a qualitative match to that inferred from transit timing variations, with a minority of non-zero eccentricities maintained by particular configurations; (e) resonant interactions occur, both mean motion and secular, but typically without driving systemic instabilities.

### 10.11.11 Other considerations

**Planet shape** The shape of a planet distorted both by rotation and tidal potential is a triaxial Roche ellipsoid (Chandrasekhar, 1969). The longest axis is directed, to within the very small angle  $Q^{-1}/2$  rad, to the star, and the shortest along its rotation axis. For a homogeneous distribution of mass, the tidal bulge or equatorial prolateness,  $f_+$ , and the polar flattening,  $f_-$  are given by

$$f_+ = \frac{15}{4} \frac{M_{\star}}{M_p} \left( \frac{R_p}{a} \right)^3, \quad f_- = \frac{25}{8} \frac{M_{\star}}{M_p} \left( \frac{R_p}{a} \right)^3. \quad (10.81)$$

These tidal bulges are typically too small to be relevant in deriving, e.g., volume or density estimates for transiting planets (e.g. Correia & Rodríguez, 2013). For example, for CoRoT-7 b ( $R_p = 1.68R_{\oplus}$ , Léger et al. (2009) estimated  $f_+ < 0.016$  and  $f_- < 0.013$ , limits which correspond to a tidal bulge of  $\pm 70$  km, and a polar radius  $\sim 120$  km smaller than its mean equatorial radius.

Higher-order effects arise from differentiated inhomogeneous bodies or non-synchronous rotation (e.g. Folonier et al., 2015).

**Constraints on planet mass and radius** For close-in planets, observed values of  $e$  can provide constraints on the planet’s mass and radius, although such inferences rely on an assumed value for  $Q_p$ . From Equation 10.72, the smaller the value of  $M_p$ , the more rapidly the tide raised on the planet can circularise its orbit, an argument used by Trilling (2000) to provide lower mass limits for a number of planets with significant eccentricities. Bodenheimer et al. (2003) used a similar argument to constrain planetary radii, given that the rate of circularisation increases with increasing  $R_p$ .

**Tides and obliquities** Measures of (sky-projected) stellar obliquities provide constraints on planet formation scenarios, and tidal evolution plays a role in their interpretation. Many hot Jupiters have large spin–orbit misalignments, with indications that at least a subset are formed with broadly-distributed obliquities, but those of the cooler stars are subsequently reduced by tidal dissipation (§6.18.7). For 53 systems, Albrecht et al. (2012b) used the estimates of Zahn (1977) for tidal synchronisation time scales due to equilibrium and dynamical tides, for cooler and hotter stars, respectively, and argued that aligned systems are those in which the time scale for spin–orbit alignment is shorter than the age.

If stellar tidal dissipation is effective in reducing obliquities, there is also the prospect that the planet will also undergo orbital decay and be destroyed. However, from Equations 10.70 and 10.73, and their generalisations to arbitrary obliquity (e.g. Lai, 2012), there are two situations in which alignment can proceed more rapidly than orbital migration. First, if  $L_s \ll L_o$ , then alignment can be faster because it involves mainly a change in the stellar spin axis, while the orbit is hardly affected. Second, if the tidal response to one or more of the  $n = 0$  components (which are associated with a torque but no power, and so do not affect  $a$ ) is much stronger, then alignment can be accelerated (Lai, 2012).

**Individual systems** Many systems, due to their brightness, close orbits and/or mass, have been the subjects of detailed tidal modeling. Among radial velocity systems (Appendix C) these include:  $\nu$  And; 51 Peg; 61 Vir; GJ 581; GJ 667C.

Among transiting systems (Appendix D) systems which have been considered in detail include: 55 Cnc; several CoRoT systems notably CoRoT-7; GJ 436; GJ 1214; several HAT systems notably HAT-P-7, HAT-P-13; HD 80606; HD 189733; HD 209458; some Kepler systems notably Kepler-10, Kepler-62; OGLE-TR-56; and many WASP systems, notably WASP-4, WASP-12, WASP-18, WASP-19, WASP-33, WASP-43.

**Algorithmic implementation** Of various routines described, Mercury-T is an open-source addition to the symplectic Mercury N-body code (box, page 513). It takes into account tides, general relativity, and rotation-induced flattening. It uses a standard equilibrium (constant time lag) tidal model, and includes the radius evolution of the host body. It is described, and applied to the 5-planet system Kepler-62, by Bolmont et al. (2015).

## 10.12 Planets in multiple star systems

**Introduction** Planet formation around binary stars,<sup>8</sup> whether circumprimary, circumsecondary, or circumbinary, is considered to follow the same precepts as for planetary formation around single stars: starting with the formation of an associated circumstellar (or circumbinary) disk as a by-product of star formation, with subsequent planet formation developing within the disk.

Various factors complicate this picture: more complex gravitational forces (and stellar irradiation) acting on the disk, planetesimals and planets, more com-

plex tidal forces, and more complex resonant behaviour. Conditions can span a vast range of environments, from very close short orbital period binaries, in which planet formation may be strongly affected by the binary companion, or even inhibited entirely, to wide separation binaries in which planet formation and long-term evolution around the primary (or secondary) may proceed more-or-less as for isolated single stars.

The study of planets in multiple star systems poses numerous challenges: of observability (presenting specific challenges for each detection method, as detailed under each technique), of quantifying their dynamical stability, and of understanding their origin.

This section summarises the occurrence and characteristics of stellar binaries, followed by those principles relevant to the formation and stability of planets around binary stars, and examples of the multiple systems discovered. Other sections which deal with binary and multiple stars include:

- radial velocity surveys around binary stars (§2.13);
- expected detection from Gaia astrometry (§3.9.2);
- detection by eclipsing binary timing residuals (§4.4);
- transit discoveries from Kepler (§6.31);
- imaging searches around binary stars (§7.9.4);
- binary stars with debris disks (§10.6.3);
- habitability around binary star systems (§11.7.1).

**Scientific interest** The scientific interest of multiple stars ranges from statistics of their physical properties (periods, mass ratios, eccentricities) providing constraints on theoretical models of star formation, various aspects of stellar evolution and mass transfer, and their central role for stellar mass determination. Understanding the occurrence of *planets* in multiple star systems, and how their frequency and properties compare with those of planets around single stars, throws much light on the formation of both stars and planets.

**Two approaches to characterisation** Assessing the occurrence of planets in multiple star systems, or assessing the stellar multiplicity of stars around which planets are known to exist, is approached from two directions.

Known binary or multiple stars can themselves be surveyed for the presence of planets, an approach which is described separately for radial velocity observations (§2.13), and for photometric transit observations (§6.3). Certain selection effects may follow. For example, although a large fraction of stars are known to occur in binary or multiple systems, radial velocity observations have tended to avoid close binaries in view of additional complexities of the spectral line calibration and analysis. For transit searches, finding and validating aperiodic transit signatures (due to the orbital motion of the host star) is more complex than for periodic signatures which (in the main) accompany single stars. Most discoveries in this category have been from radial velocity

<sup>8</sup> In general here, the term ‘binary star’ should be understood as including systems of higher multiplicity (triples, quadruples, etc.) although binary systems currently dominate. Similarly, the term ‘multiple stars’ will generally embrace binary systems. Circumprimary will frequently be used as shorthand for ‘circumprimary or circumsecondary’ in contrast to ‘circumbinary’. Generally, the precise meaning should be clear in context.

surveys, with about a dozen circumbinary systems discovered from Kepler transit photometry.

The other approach is to scrutinise stars around which planets have already been discovered, in order to determine whether the star has other widely separated or fainter stellar mass companions which, typically, will not have compromised the initial discovery (§7.9.4). Observations include high angular resolution imaging to probe separations out to a few arcsec, or the imaging search for more widely separated companions out to 100 arcsec or more, often corresponding to stellar component separations of 100–1000 au or more. In either case, to ensure their apparent physical association is real, the classification of candidate companions requires confirmation that the components share the same proper motion, i.e. that they form a *common proper motion pair*.

As a consequence of these various complexities, a detailed statistical picture of the occurrence of planets around binary or multiple star systems is currently highly incomplete.

**Discovery techniques** Circumbinary and/or circumprimary planets have been detected using all discovery techniques available, with the exception of astrometry: many by their radial velocity signatures (§2.13), others by transit photometry, starting with Kepler–16AB (§6.3), by varying eclipse times in eclipsing binaries, such as NN Ser (§4.4), by microlensing surveys, such as OGLE–2007–BLG–349L(AB) (§5.10.1), and by direct imaging, e.g. Ross 458, a planetary-mass object around an M dwarf binary (§7.9.4).

In addition, there are planet-forming protoplanetary disks and debris disks around binary star systems (§10.6.3), and a Jupiter-mass planet orbiting a degenerate pulsar/white-dwarf binary (PSR B1620–26).

### 10.12.1 Binary and multiple stars

**Occurrence rates** That the majority of solar-type stars appear to reside in binary or multiple systems has been known for some time (e.g. Abt, 1979). Nearby G-K dwarfs, for example, which have been high-priority targets for many radial velocity programmes, are known to occur more often in binary or multiple systems than in isolation (e.g. Duquennoy & Mayor, 1991; Mathieu, 1994; Eggenberger et al., 2004a; Duchêne & Kraus, 2013), although arriving at precise fractions remains troublesome (e.g. Whitworth & Lomax, 2015).

More broadly, some 70% of main and pre-main sequence stars are members of binary or multiple star systems (e.g. Abt & Levy, 1976; Duquennoy & Mayor, 1991; Tohline, 2002; Halbwachs et al., 2003; Tokovinin et al., 2006; Raghavan et al., 2010).

In multiple *stellar* systems, co-planar systems are rare. Of the 2413 systems in the Sixth Catalogue of Orbits

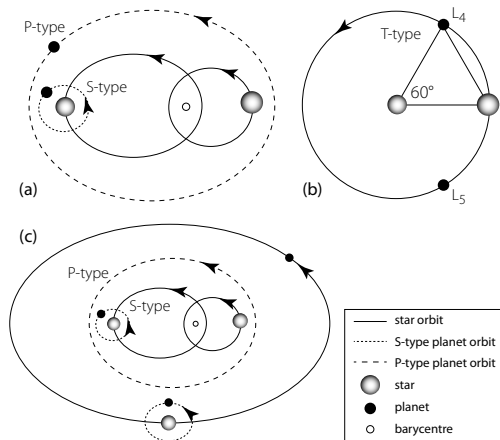


Figure 10.48: (a) Schematic of a binary star system showing planets occupying an S-type orbit around one of the stars, or a P-type circumbinary orbit about both stellar components. (b) A T-type orbit around one of the Lagrange points L4 or L5. (c) The different dynamical possibilities for planetary orbits in a triple star system. Adapted from Schwarz et al. (2011, 2016b).

of Visual Binary Stars (Hartkopf et al., 2001) 48 have all seven Campbell elements for both inner and outer systems in hierarchical arrangements. Of these, only four have the possibility of being co-planar according to the precepts of Fekel (1981).

**Binary star characteristics** The formation of binary and multiple stars is considered as occurring in two principal phases: fragmentation of molecular clouds producing the condensing cores, followed by subsequent accretion and migration which will fix the final component masses and orbital parameters (e.g. Halbwachs et al., 2003; McKee & Ostriker, 2007).

Stellar systems composed of two or more stars (binaries or multiples) exist in a wide range of configurations. They range from tight binaries with orbital periods of hours or days, and separations down to less than  $10R_{\odot}$  ( $\sim 0.1$  au), to marginally-bound wide binaries with orbital periods  $> 10^5$  yr and separations up to 20 000 au (0.1 pc) or more.

Although stellar binaries (and higher multiplicities) are extremely common, the true binary frequency is hard to establish for any given population due to the different techniques required to probe different separation ranges, and to the inherent difficulties of detecting binaries with very small or very large angular separations, or large magnitude differences. Binary frequency appears to correlate well with stellar ages: e.g., low-mass pre-main-sequence stars in the star-forming region Taurus–Auriga have an (inferred) binary frequency as high as 80–100% (Leinert et al., 1993; Kohler & Leinert, 1998), values confirmed by studies of other star-forming regions.

Studies of component mass ratios give different results according to observational technique and sample population (e.g. Cumming et al., 2008; Raghavan et al., 2010; Reggiani & Meyer, 2011; Janson et al., 2012c; Reggiani & Meyer, 2014). A bimodal distribution is often reported, with one peak arising from equal-mass components, and another at a mass ratio of around 0.2–0.3. The distribution in orbital period  $P$  extends over several orders of magnitude, from days to several Myr (Duquennoy & Mayor, 1991; Fischer & Marcy, 1992).

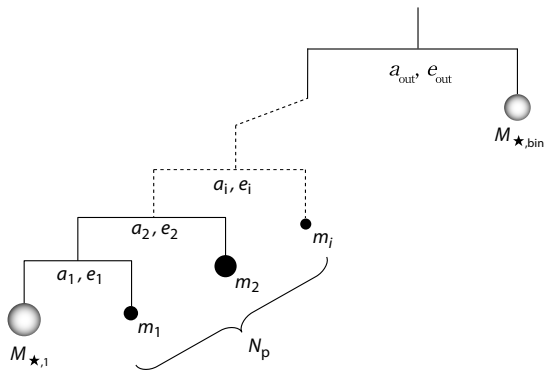


Figure 10.49: ‘Mobile diagram’ of a hierarchical multi-planet system in a stellar binary. Here, the  $N_p = 3$  planets orbit a star with mass  $M_{*,1}$ . The centre of mass of this subsystem is orbited by a binary companion star with mass  $M_{*,bin}$  in an orbit with semi-major axis and eccentricity  $a_{out}$  and  $e_{out}$ . From Hamers & Portegies Zwart (2016a, Figure 10), © Oxford University Press.

Spectroscopic binary periods display a bell-shaped distribution in  $\log P$ , with a maximum in the visual binary range at around 180 yr (e.g. Goldberg et al., 2003). Eccentricity is correlated with period: circular orbits dominate for  $P \lesssim 10$  d, with longer-period systems having eccentricities ranging from 0.1 to nearly 1.0, and with an absence of circular orbits.

**Occurrence of disks and planets** As for single stars (§10.3) many young binaries are known to possess disks, either *circumstellar* (around one of the stars) or *circumbinary* (around both) which, in analogy with single stars, may provide the accretion material for planet formation (e.g. Mathieu, 1994; Akeson et al., 1998; Mathieu et al., 2000; White & Ghez, 2001; Monin et al., 2007).

There is also substantial evidence for debris disks, not only around single stars, but also around main sequence binaries (§10.6). These findings implied, in turn, that planet formation may be common around binary stars (e.g. Mathieu, 1994; Akeson et al., 1998; Rodríguez et al., 1998; Trilling et al., 2007).

### 10.12.2 Planet configurations and stability

**Possible configurations** Studies of dynamical configurations for planets in binary systems were carried out well in advance of the first detections. Szebehely (1980) classified the possibilities as ‘inner orbits’ revolving around the primary, ‘satellite orbits’ revolving around the secondary, or ‘outer orbits’ revolving around both.

From the stability of periodic orbits in the circular restricted three-body problem, Dvorak (1982) suggested that a planet may exist in either a circumstellar orbit, i.e. orbiting either the primary or secondary star (also referred to as an *S-type orbit*, for ‘satellite’), or in a circumbinary orbit, i.e. orbiting both stars (*P-type*, for ‘planetary’). These are shown schematically in Figure 10.48a. Existence in a 1:1 ‘Trojan’ resonance around the L4 or

L5 Lagrange points (*T-type*, or occasionally indicated *L-type*) is also possible dynamically (Figure 10.48b). A schematic of the various possible planetary orbits in triple star systems is shown in Figure 10.48c.

More complex systems composed of nested binaries orbited by (perhaps multiple) multi-planet systems can conveniently be represented by ‘mobile’ diagrams, introduced by Evans (1968), used by e.g. Hamers & Portegies Zwart (2016a), and illustrated in Figure 10.49.

**Dynamical stability** The definition of dynamical stability of a planetary orbit in a binary system was already considered by various early authors (e.g. Harrington, 1977; Szebehely, 1980, 1984), following similar considerations for multi-planet systems (§2.12.1). Harrington (1977) considered the orbit as stable if  $a$  and  $e$  do not undergo secular changes. More pragmatically, Haghighipour (2008) considered it stable if, over some extended duration, it does not collide with other bodies, and it does not leave the system’s gravitational field.

With the more limited numerical tools available, early stability studies were restricted to special cases, or only a few orbital periods (Graziani & Black, 1981; Black, 1982; Pendleton & Black, 1983). In particular with the advent of symplectic integrators (box, page 513), orbits of low-mass bodies in binary systems could be followed over much longer intervals (e.g. Chambers et al., 2002). The long-term stability of planets in various S-type and P-type orbits, at least within certain domains, has been confirmed by such dynamical studies.

**Stability of circumprimary orbits** For a planet in a circumprimary (or circumsecondary, i.e. S-type) orbit, the gravitational force of the other star is the principal source of orbit perturbations. Qualitatively, the perturbative effect varies with the companion star mass, and according to the eccentricity and semi-major axis of the binary which together determine the closest approach of the secondary to the planet.

From direct dynamical simulations of test particles (Rabl & Dvorak, 1988; Holman & Wiegert, 1999; Haghighipour, 2008), the maximum value of the semi-major axis of a stable planetary orbit can be approximated as (Holman & Wiegert, 1999, equation 1)

$$a_c/a_b = (0.464 \pm 0.006) + (-0.380 \pm 0.010)\mu \\ + (-0.631 \pm 0.034)e_b + (0.586 \pm 0.061)\mu e_b \\ + (0.150 \pm 0.041)e_b^2 + (-0.198 \pm 0.047)\mu e_b^2, \quad (10.82)$$

where  $a_c$  is the critical semi-major axis,  $a_b$  and  $e_b$  are the semi-major axis and eccentricity of the binary,  $\mu = M_1/(M_1 + M_2)$ , and  $M_1$  and  $M_2$  are the masses of the primary and secondary stars. The  $\pm$  signs together define a transitional region, comprising a mixture of stable and unstable states, where stability depends on orbital parameters, mass ratio, and initial conditions. Slightly



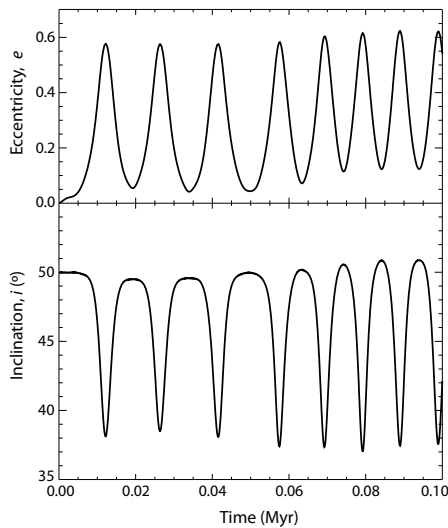


Figure 10.50: Eccentricity and inclination variations for a test particle undergoing Lidov–Kozai oscillations. The configuration is for the system  $\gamma$  Cep, with starting elements  $a = 0.5$  au and  $i = 50^\circ$ :  $e$  and  $i$  oscillate strongly,  $180^\circ$  out of phase. From Verrier & Evans (2006, Figure 3), © Oxford University Press.

different limits have been found in later studies (Moriwaki & Nakagawa, 2004; Fatuzzo et al., 2006).

Such results are applicable to planets of terrestrial and Jupiter mass (e.g. Quintana et al., 2002; Quintana & Lissauer, 2006; Quintana et al., 2007) and, discounting the effects of radiation pressure, to dust particles and debris disks (e.g. Trilling et al., 2007).

Numerous other stability and dynamical studies for S-type systems have been reported, both for general cases (e.g. Benest, 1993; Pilat-Lohinger & Dvorak, 2002; David et al., 2003; Musielak et al., 2005; Mudryk & Wu, 2006; Cuntz et al., 2007; Marzari & Barbieri, 2007b,a; Sepinsky et al., 2007; Szenkovits & Makó, 2008; Plávalová & Solovaya, 2013; Marzari & Gallina, 2016; Veras, 2016a; Voyatzis, 2017). and for many specific systems, amongst the first being  $\alpha$  Cen (Benest, 1988; Wiegert & Holman, 1997), Sirius (Benest, 1989),  $\eta$  CrB (Benest, 1996), and  $\gamma$  Cep (Dvorak et al., 2003a, 2004a; Haghighipour, 2006; Verrier & Evans, 2006). Others are detailed in Appendix C and D.

**Lidov–Kozai resonance** A specific dynamical effect observed in simulations of S-type binaries is the phenomenon of *Lidov–Kozai oscillation* or *Kozai resonance*, detailed in Section 10.10.6. In three-body systems with two massive objects and a smaller body in a highly inclined orbit, such as in the case of a binary–planet system, angular momentum exchange between the planet and the secondary star results in the planet’s inclination and eccentricity oscillating synchronously, i.e. increasing one at the expense of the other.

This behaviour, in which  $e$  and  $i$  oscillate with the same periodicity but  $180^\circ$  out of phase, is seen in general numerical simulations of S-type systems (Takeda & Rasio, 2006; Takeda et al., 2008a; Zhao et al., 2012a), as

well as for individual systems such as  $\gamma$  Cep (Haghighipour, 2004, 2006; Verrier & Evans, 2006, Figure 10.50).

In multi-planetary systems with highly inclined orbits, Lidov–Kozai oscillations can result in highly eccentric outer planets. If their orbits cross the inner planets, strong planet–planet interactions can result in the ejection of one or more of the planets (Malmberg et al., 2007a; Parker & Goodwin, 2009; Verrier & Evans, 2009).

Related behaviour is found in the case of a high-inclination planet in a circumbinary orbit around a tight stellar binary, in which the outer (low-mass) object can excite a large eccentricity of the inner binary (Migaszewski & Goździewski, 2011).

**Stability of circumbinary orbits** Analogous to circumprimary orbits (Equation 10.82), P-type planetary orbits are found to be stable for semi-major axes exceeding a critical value (Dvorak et al., 1989; Holman & Wiegert, 1999; Haghighipour, 2008). Results from regression of a second-order polynomial to a suite of dynamical simulations show that this condition can be approximated by (Holman & Wiegert, 1999, equation 3)

$$a_c/a_b = (1.60 \pm 0.04) + (4.12 \pm 0.09)\mu + (5.10 \pm 0.05)e_b \\ + (-4.27 \pm 0.17)\mu e_b + (-2.22 \pm 0.11)e_b^2 \\ + (-5.09 \pm 0.11)\mu^2 + (4.61 \pm 0.36)e_b^2\mu^2. \quad (10.83)$$

Orbits are unstable inside this critical radius, and any particles are cleared, creating a cavity around the binary.

Inclined systems can remain stable on shorter orbits (Pilat-Lohinger et al., 2003), as can retrograde orbits (Morais & Giuppone, 2012).

In addition, numerical simulations show islands of (in)stability that appear in specific configurations (Hénon & Guyot, 1970; Dvorak, 1984; Rabl & Dvorak, 1988; Dvorak et al., 1989), which arise from first-order mean motion resonances (Holman & Wiegert, 1999; Verrier & Evans, 2006), and which are therefore not captured by the Holman–Wiegert analytical fit (Equation 10.83). Lam & Kipping (2018) applied a ‘deep learning’ algorithm based on neural networks (§6.12.3), and trained on N-body simulations generated with REBOUND (§10.6.3), to improve stability predictions for circumbinary planets on initially coplanar, circular orbits.

Further details of the theory of satellite orbits about a central binary, based on the restricted three-body problem (e.g. Lee & Peale, 2006; Leung & Lee, 2013), are described by, e.g., Bromley & Kenyon (2015).

Many detailed simulations and studies of circumbinary planet stability in binary and multiple star systems have been made, including chaotic orbits, orbital precession, and more complex configurations such as orbits around eccentric protoplanetary disks (e.g. Zigelin, 1975; Szebehely & McKenzie, 1981; Dvorak, 1984, 1986; Dvorak et al., 1989; Kubala et al., 1993; Holman & Wiegert, 1999; Broucke, 2001; Pilat-Lohinger et al., 2003;

Musielak et al., 2005; Pierens & Nelson, 2008c; Doolin & Blundell, 2011; Morais & Correia, 2012; Saito et al., 2012a; Pelupecy & Portegies Zwart, 2013; Leung & Lee, 2013; Martin & Triaud, 2014; Chavez et al., 2015; Miranda & Lai, 2015; Oks, 2015; Silsbee & Rafikov, 2015b; Popova & Shevchenko, 2016b). Studies have also been made for polar orbits (Li et al., 2014a; Egan, 2018); multiple planets (Andrade-Ines & Robutel, 2018); tidal effects (Correia et al., 2016); and hierarchical triple systems (Verrier & Evans, 2007; Domingos et al., 2012; Xiang-Gruess & Papaloizou, 2014).

A Hamiltonian-based secular-dynamical model for systems composed of nested binaries, with an arbitrary number of bodies and an arbitrary hierarchical structure, is described by Hamers & Portegies Zwart (2016a), and applied to the planet which orbits one binary component of the (2+2) quadruple stellar system 30 Ari.

Kostov et al. (2016a) found that future effects of the post-common-envelope evolutionary phase (box, page 113) on systems such as Kepler-47 provide a reasonable match to the corresponding eclipse-time variation candidates, such as V471 Tau and NN Ser (§4.4.2).

**Non-Keplerian orbits** Particles beyond the critical distance can also be on stable, non-Keplerian orbits (Bromley & Kenyon, 2015). In addition to their response to the central mass of the binary, these particles also experience forced motion, driven by the binary's time-varying potential, which prevents them from maintaining circular or eccentric orbits. Instead, they may achieve a 'most circular orbit', defined as having the smallest radial excursion about some guiding centre, orbiting at some constant radius  $R_g$  and angular speed  $\Omega_g$  in the plane of the binary (Lee & Peale, 2006; Youdin et al., 2012). More generally, eccentric circumbinary orbits may be composed of epicyclic motion about  $R_g$  superimposed on the most circular orbit.

### 10.12.3 Planet formation in multiple star systems

Planet formation relies on solid particles (dust, planetesimals, and protoplanets) being able to interact 'gently'. Around a single star, circular co-planar orbits provide the environment in which growth can proceed through gravitational interactions, with dynamical cooling (collisional damping, dynamical friction, or gas drag) necessary to limit collisional destruction. Growth proceeds through coagulation of dust particles and their growth to cm-size objects; collisional growth to km-size planetesimals; the coalescence of planetesimals to form protoplanets or planet embryos; and their collisional growth to form terrestrial-size objects.

These processes can be dramatically modified in both circumprimary and circumbinary configurations, and over a wide range of systems parameters.

**Circumprimary formation** For circumprimary planets, the secondary star can have a significant effect on each of these sequential processes. Various studies and simulations have been made.

These include: • dynamics of moderate- (Lubow & Martin, 2016) and high-inclination systems (Pfahl & Mutterspaugh, 2006; Pascucci et al., 2008; Marzari et al., 2009; Xie et al., 2011); • particle accretion and migration (Marzari & Scholl, 2000; Paardekooper et al., 2008; Xie & Zhou, 2008; Paardekooper & Leinhardt, 2010; Fagnier et al., 2011; Giuppone et al., 2011; Zsom et al., 2011b; Alexander, 2012; Rivier et al., 2012; Jang-Condell, 2015; Rafikov & Silsbee, 2015a,b); • effects on protoplanets (Tsukamoto & Makino, 2007; Payne et al., 2009b); • terrestrial planet formation (Barbieri et al., 2002; Quintana et al., 2002; Lissauer et al., 2004); • habitable planets and environments (Haghighipour & Raymond, 2007; Bancelin et al., 2015; Cuntz, 2014, 2015; Johnstone et al., 2015; Mason et al., 2015a).

For orbits around one component of a binary, Quintana et al. (2007) already showed that sufficiently wide binaries leave planet formation largely unaffected. Binary stars with pericentre  $q_b \equiv a_b(1 - e_b) > 10$  au have a minimal effect within  $\sim 2$  au of the primary, whereas those with  $q_b \lesssim 5$  au restrict terrestrial planet formation to within  $\sim 1$  au of the primary. Given the distribution of binary orbits for solar-type primaries, they estimated that  $\sim 40$ – $50\%$  of the binary population would allow terrestrial planet formation to take place unimpeded.

The existence of additional stellar companions may inhibit the formation of circumstellar giant planets with particular orbital separations. Thus Nelson (2000) found that planet formation is unlikely in equal-mass binary systems with  $a \sim 50$  au; Mayer et al. (2005) considered the effects of modified gravitational instabilities; and Thébault et al. (2006) considered regions in  $a \lesssim 50$  au systems in which runaway accretion is strongly affected.

A stellar component on an eccentric orbit can truncate the circumprimary disk to smaller radii, and remove material otherwise available for terrestrial planet formation (Artymowicz & Lubow, 1994; Pichardo et al., 2005). More distant but highly inclined companions can modify their orbits over long time scales (Innanen et al., 1997; Takeda & Rasio, 2005). During protoplanet formation, perturbation of the secondary may increase the relative velocities of planetesimals, resulting in greater fragmentation, or creating regions where the orbits are unstable and so emptied of accretion material (Heppenheimer, 1978; Whitmire et al., 1998; Thébault et al., 2004).

A binary companion can modify the structure of a planet-forming nebula, and create regions where gas and dust densities are locally enhanced. In turn, this may augment planet formation around the primary by gravitational instability (Mayer et al., 2005; Boss, 2006a), or by core accretion (Thébault et al., 2004).

**Circumbinary formation** For formation of a circumbinary planet, the central binary also dramatically alters these orbital dynamics, restricting accretion regions and creating specific morphologies such as warps, but nonetheless provides an environment in which planetary systems can form and survive robustly. Various studies and simulations have been made.

These include: • stability (Dvorak, 1986; Rabl & Dvorak, 1988; Dvorak et al., 1989; Holman & Wiegert, 1999; Musielak et al., 2005; Doolin & Blundell, 2011; Gong, 2017); • formation (Bonnell & Bate, 1994; Pichardo et al., 2005; Quintana & Lissauer, 2006; Martin et al., 2013; Pelupessy & Portegies Zwart, 2013; Rafikov, 2013a,b; Bromley & Kenyon, 2015); • disk properties (Scholl et al., 2007; Meschiari, 2012b; Clanton, 2013; Facchini et al., 2013; Foucart & Lai, 2013; Demidova & Shevchenko, 2015; Silsbee & Rafikov, 2015a; Vartanyan et al., 2016; Mutter et al., 2017b; Thun et al., 2017).

Acting to inhibit planet formation in a circumbinary disk, these numerical studies of planetesimal growth show that formation is generally hindered by effects such as raised planetesimal velocities out to several au, which would include the *present* orbits of the known circumbinary planets. Although *in situ* growth in such hostile environments may therefore be unlikely, planets can still form further out, early in the lifetime of the protoplanetary disk, subsequently migrating inwards with associated damping of eccentricities, and frequently leaving the final orbit close to the critical limit for dynamical stability given by Equation 10.83 (Pierens & Nelson, 2007, 2008c,b; Paardekooper et al., 2012; Pierens & Nelson, 2013; Kley & Haghighipour, 2014; Silsbee & Rafikov, 2015a; Pierens & Raymond, 2016).

As for circumpriary models, planet formation in circumbinary disks may actually be assisted by zones of lower velocity (Martin et al., 2013; Rafikov, 2013a; Bromley & Kenyon, 2015). The observed occurrence rate of circumbinary planets provides a guide to the importance of these types of effect. With the inclusion of migration, numerical simulations indicate that circumbinary planets should be common, and typically smaller than Jupiter (Kostov et al., 2016b).

Observationally, the orbits of the circumbinaries Kepler–16 b, Kepler–34 b, Kepler–35 b and Kepler–38 b are indeed outside the critical orbital semi-major axis, by some 21%, 24%, 14% and 26% respectively (Welsh et al., 2012; Orosz et al., 2012b). Kepler–47 b lies further from the instability region (Orosz et al., 2012a).

### 10.12.4 Discoveries

The on-line catalogue of exoplanets in binary and higher multiplicity star systems (Table 1.4) lists, at the end of 2017, 122 planets in 87 binary systems, and a further 34 planets in 24 higher multiplicity systems.

Planets in binary systems have been found both in *S-type* orbits, where the planet orbits one of the two stars (circumprimary or circumsecondary) with an orbital period much shorter than the binary, and in *P-type* orbits, where the planet orbits the entire binary (circumbinary) with a period much longer than that of the binary.

Most known binary system planets are in *S-type* orbits, and most of these have been discovered from radial velocity studies (e.g. Pilat-Lohinger & Dvorak, 2002; Pilat-Lohinger et al., 2003; Haghighipour, 2010).

The stellar separations of many of these binaries exceed 100 au, implying that the perturbation of their more distant stellar companions on the formation and dynamical evolution of planets around their planet-hosting stars may be negligible.

Radial velocity surveys have identified a few binary systems with smaller separations of around 20 au where one of the stars is host to a Jovian-type planet, including GJ 86 (Queloz et al., 2000b; Els et al., 2001),  $\gamma$  Cep (Hatzes et al., 2003a), HD 41004 (Zucker et al., 2004; Raghavan et al., 2006), HD 196885 (Correia et al., 2008b), and HD 176051 (Mutterspaugh et al., 2010b). In addition, various circumbinary planets around eclipsing binaries have been discovered from timing studies (Chapter 4).

Some dozen planets in binary systems have been found from ground-based transit surveys, mostly *S-type*, including: HAT-P-1, HAT-P-32, HAT-P-33; KELT-2, KELT-4; TrES-2, TrES-4; WASP-2, WASP-11, WASP-20, WASP-70, WASP-77, WASP-85, WASP-94; and XO-2.

Circumbinary planets around *normal* stars were first found with Kepler, with the discovery of Kepler–16(AB) b (Doyle et al., 2011). A number of other such Kepler circumbinary systems are now known. Selection effects in the discovery and characterisation of these systems is considered by Li et al. (2016a). No *S-type* (circumprimary) planets have yet been discovered from Kepler, or in general in eclipsing binary stars, in part reflecting practical difficulties in discovery (§6.12.3).

**Follow-up surveys for host star multiplicity** Meanwhile, from follow-up searches of known exoplanet host stars for close binary companions (§7.9.3), the fraction of exoplanet hosts that are single, binary, or multiple, has been variously estimated at 77%, 20%, and 3% respectively by Raghavan et al. (2006); 83%, 15%, and 2% respectively by Mugrauer & Neuhäuser (2009); and 88%, 10%, and 2% respectively by Roell et al. (2012).

The implications of these large-scale follow-up surveys for stellar companions formation, combined with formation and stability models around multiple star systems is only now starting to emerge. For example, Kraus et al. (2016) found that if the binary population is parameterised with a semi-major axis cut-off  $a_{\text{cut}}$ , and a suppression factor inside that cut-off  $S_{\text{bin}}$ , then with correlated uncertainties that inside  $a_{\text{cut}} = 47^{+59}_{-23}$  au, the planet occurrence rate in binary systems is  $S_{\text{bin}} = 0.34^{+0.14}_{-0.15}$  times that of wider binaries or single stars, suggesting that one fifth of all solar-type stars are unable to host planetary systems due to the influence of a binary companion.

Multiplicity data remains inadequate in the region of particular interest, 1–100 au (e.g. Wang et al., 2015d), while in the range 100–2000 au observed stellar multiplicity rates are comparable for single transiting planet systems ( $6.4 \pm 5.8\%$ ), multiple transiting planet systems ( $8.0 \pm 4.0\%$ ), and their control sample ( $12.5 \pm 2.8\%$ ).

### 10.12.5 Individual systems

As well as studies and simulations undertaken for many specific systems, detailed in Appendix D, and few systems have been considered, from the perspective of formation and stability, in particular detail.

**$\alpha$  Cen** Alpha Cen is the closest star system to Earth ( $d = 1.34$  pc). It consists of three stars: the pair  $\alpha$  Cen A and  $\alpha$  Cen B, separated by 15 000 au ( $P_{\text{orb}} = 79.9$  yr,  $e = 0.52$ ), together with a faint red dwarf,  $\alpha$  Cen C (Proxima Cen), that may be gravitationally bound to the other two.

A planet orbiting  $\alpha$  Cen B was announced from 400 radial velocity observations over 4 yr with HARPS (Dumusque et al., 2012), but later attributed to signal artefacts (Rajpaul et al., 2016). A single transit-like event associated with a distinct (and unconfirmed) planet candidate,  $\alpha$  Cen Bc, was detected from 40 h of HST observations in 2013–14 (Demory et al., 2015).

Due to its proximity, and the resulting quality of observational diagnostics, the system has been intensively studied as a potential planet host, with studies of formation, dynamical stability, and habitable zones in the binary star environment, the different chemical compositions of the component stars (including Li and Be abundances), and the fundamental stellar properties including inferences from asteroseismology. A chronological synopsis of studies is given in Appendix C.

**Kepler circumbinary systems** Kepler photometry provides information on orbits, transit profiles, transit durations, and transit timing variations, phenomena widely referenced throughout Chapter 6. As a result, detailed studies of planet formation and stability have been made, for example, for:

- Kepler–16 (e.g. Meschiari, 2012a; Paardekooper et al., 2012; Marzari et al., 2013; Pierens & Nelson, 2013; Rafikov, 2013a; Meschiari, 2014; Bromley & Kenyon, 2015; Lines et al., 2015);
- Kepler–34 (Paardekooper et al., 2012; Pierens & Nelson, 2013; Lines et al., 2014; Kley & Haghighipour, 2015; Lines et al., 2015);
- Kepler–35 (Paardekooper et al., 2012; Pierens & Nelson, 2013);
- Kepler–38 (Kley & Haghighipour, 2014).

### 10.12.6 Occurrence rates

Early results suggested that the properties of planetary systems in single and binary star systems appeared to be broadly similar (Eggenberger, 2010; Raghavan et al., 2010; Lissauer et al., 2014a). Subsequent work has shown that detailed conclusions depend on binary separation, with S-type planets appearing to be less common in binary systems than similar planets around single stars (Wang et al., 2014a). Adaptive optic searches also support the idea that a stellar companion within 100 au tends to inhibit, but not entirely suppress, planet formation (Eggenberger et al., 2007a).

Wang et al. (2014b) used archival radial velocity measurements to show that the stellar multiplicity rate of planet host stars is significantly lower than field stars for  $a \lesssim 20$  au, suggesting that planet formation and evolution are suppressed by the presence of a close-in companion star at these separations.

Parker & Quanz (2013) determined the fraction of G dwarfs that could host stable planetary systems based

on the observed properties of binaries in the Galactic field, and in various postulated primordial binary populations, which generally assume that the primordial binary fraction is higher than that in the field. If assumed the same, they estimate that up to 63% of G dwarf systems could potentially host a solar system analogue, viz. planetary systems that form either around a single G dwarf, or a binary containing a G dwarf where the binary separation exceeds 100–300 au. However, if the primordial binary fraction is higher, the fraction of G dwarf systems that could host a solar system analogue is lowered to 38%. For circumprimary or circumbinary planets with separations in the range 1–100 au, they found that 65–95% of circumprimary systems can host a planet at 1 au, decreasing to 20–65% at 100 au. In the circumbinary case, between 5–59% can host a planet at 1 au, increasing to 34–75% that can host a planet at 100 au.

Armstrong et al. (2014a) made an observationally-based determination of the rate of occurrence of circumbinary planets from the Kepler data. Their predicted rates depend sensitively on the planetary inclination distribution: if circumbinary planets are preferentially co-planar with their host binaries, then the rate of occurrence of planets with  $R_p > 6R_{\oplus}$  with  $P < 300$  d is  $10.0^{+18}_{-6.5}$  %, slightly higher than but consistent with single star rates. However, if the underlying inclination distribution is isotropic, the occurrence rate rises to a lower limit of 47%. This implies that formation and subsequent dynamical evolution in circumbinary disks must either lead to largely co-planar planets, or it must actually proceed more efficiently than in circumstellar disks. They also found that giant planets ( $R_p > 10R_{\oplus}$ ) are significantly less common in circumbinary orbits than smaller planets.

The occurrence rate of circumbinary gas giants has been estimated to be of order 10% (Armstrong et al., 2014a; Martin & Triaud, 2014), similar to the abundance of gas giants orbiting single stars (Cumming et al., 2008).

### 10.12.7 Other insights

Aside from the discovery and simulations of the formation of specific systems, planets in multiple star systems offer some specific insights into the formation of both planets and binary stars more generally.

**Short-period binaries and Lidov–Kozai cycles** There is a lack of circumbinary planets around the Kepler short-period binaries,  $P \lesssim 5 - 7$  d (Armstrong et al., 2014a; Martin et al., 2015; Li et al., 2016a), despite more than half of the Kepler eclipsing systems having periods in this range. The shortest-period planet-hosting binary is Kepler–47, with  $P_b \sim 7.45$  d (Orosz et al., 2012a).

This behaviour lends additional support for the formation scenario of compact binary stars, in which a distant stellar companion drives Lidov–Kozai oscillations and subsequent tidal circularisation (§10.10.6) of

the initially wide host binary star towards its current close configuration (Mazeh & Shaham, 1979; Fabrycky & Tremaine, 2007; Martin et al., 2015; Muñoz & Lai, 2015; Hamers et al., 2016; Martin & Triaud, 2016). This process would probably remove any planets initially orbiting one of the two stars, with the consequence that planets, either S-type or P-type, would not be expected in binary systems with periods of a few days or less.

**Time-varying irradiation and stellar winds** A circumbinary planet orbiting two host stars will experience time-varying irradiation of its atmosphere. For a close, short-period binary, rapid stellar rotation causes a permanent state of high stellar activity and ultraviolet radiation which can be particularly efficient in evaporating the planet's atmosphere (Sanz-Forcada et al., 2014). Similar effects arise from their colliding stellar winds, generating shocks and regions of enhanced density and temperature (Johnstone et al., 2015). For typical circumbinary planets on stable orbits, May & Rauscher (2016) used general circulation models (box, page 593) to examine temperatures with respect to the equivalent single star case, finding only small differences, insufficient to excite different circulation patterns.

**Constraints on binary star formation** In addition to constraints on the origin of compact stellar binaries, circumbinary systems offer other specific insights into the formation of the binary stars themselves (Tohline, 2002). For example, at the most basic level, if binary stars form through dynamical interactions between single stars in a dense gas-free cluster, it would be difficult for them to acquire circumbinary planets. Conversely, if they form through fragmentation and collapse in a gas-rich environment, they are likely to acquire a circumbinary disk in which planets could form.

The frequency of planets in binaries with small separation may also be strongly reduced if the pair was, in the past, in a temporary inclined hierarchical triple configuration (Marzari & Barbieri, 2007a),

**Dynamical packing** The dynamically-packed systems discovered in large number by Kepler are providing considerable insight into the origin and evolution of planetary systems (§6.30.3). Dynamical packing in circumbinary systems has been considered by Kratter & Shannon (2014). While they found that the existing Kepler data are insufficient to distinguish between a population of packed or sparse circumbinary systems, results from the TESS mission, combined with a study of circumbinary transit timing variations, provide opportunities for increasing the relevant sample size.

**Co-planarity of multi-planet binary systems** The general topic of co-planarity of Kepler *multi-planet* systems orbiting *single* stars is discussed in Section 6.30.5.

For circumbinary planets, simulations suggest that their orbits are likely to be co-planar (within a few de-

grees), at least for binary stars with sub-au separation, due to disk–binary alignment on precession time scales (Foucart & Lai, 2013, 2014).

For the (mostly single) planets around multiple (mostly binary) star systems, the hierarchical planet–binary systems are indeed found to be rather co-planar (Martin & Triaud, 2015), and not easily attributable to selection effects (Li et al., 2016a). Co-planarity is specifically discussed for Kepler–16 (Doyle et al., 2011), Kepler–34 (Welsh et al., 2012), Kepler–35 (Welsh et al., 2012), Kepler–38 (Orosz et al., 2012b), Kepler–47 (Orosz et al., 2012a), Kepler–64 (Schwamb et al., 2013).

Slight misalignments between the planet and binary orbits are observed for Kepler–413,  $\sim 2^\circ 5$  (Kostov et al., 2014), and Kepler–453,  $\sim 2^\circ 25$  (Welsh et al., 2015). Such misalignments must be considered in any estimates of the circumbinary population frequency (e.g. Armstrong et al., 2014a; Martin & Triaud, 2014).

**Scattered, flipping, and jumping planets** Planet–planet scattering in multi-planet systems, resulting in eccentric and misaligned planets, is likely to exist in circumbinary systems just as it does in single star systems (§10.10.4). Multi-body dynamics may lead to a wide variety of configurations (e.g. Leung & Lee, 2013; Sutherland & Fabrycky, 2016; Smullen et al., 2016), including more exotic scenarios such as orbit ‘flipping’, by  $\sim 180^\circ$ , as it ‘rolls over’ its major axis (Li et al., 2014c), and the exchange (also described as the ‘jumping’, ‘hopping’, or ‘bouncing’) of planets between stellar components (Kratter & Perets, 2012; Moeckel & Veras, 2012).

Such an origin has been postulated for the hot Jupiters orbiting the two components of the WASP–12 stellar binary system (Neveu-VanMalle et al., 2014).

**Giant branch and white dwarf phases** Planet ejection may also occur during the transition between the giant branch and white dwarf phases of the primary system (Veras et al., 2017b). A binary companion within some  $7\times$  the outer planet separation can trigger instability in an otherwise stable single-star two-planet system during these phases, affecting the system architecture, and perhaps generating observable metal pollution in the white dwarf atmosphere (§8.9.4).

**Circumbinary protoplanetary disks** The detections and monitoring of *winking binaries*, KH 15D (Winn et al., 2006a, 2004a, 2006a); WL 4 (Plavchan et al., 2008a); YLW 16A (Plavchan et al., 2013b), indicate that they are composed of a binary surrounded by an optically thick and inclined protoplanetary disk. The disk is warped and precesses due to the torques exerted by the binary, and the precession modulates the light obscured by the disk and causes the ‘winking’ (Winn et al., 2006a). Some binary stars have spin axes inclined with respect to their orbital spin (e.g. Albrecht et al., 2009; Zhou & Huang,

2013; Albrecht et al., 2014) and may reflect the same processes that lead to inclined disks.

Proto-binaries formed by fragmentation are believed to have an initial separation larger than 10 au, with typical separations larger than 100 au (Bate, 2012). Migration of both components is therefore required to form closer binaries, which can occur under certain disk conditions for an accreting binary (Artymowicz & Lubow, 1996). Foucart & Lai (2013) found that during mass accretion, angular momentum gets redistributed leading the binary and disk planes to align. Their corollary is that relatively short period binaries (sub-au) will only harbour co-planar circumbinary planets, because they would likely form after the binary migration and thus, after the disk has realigned.

Lodato & Facchini (2013) noted that the warped disk can reach a misaligned steady-state and subsequently precess as a rigid body (e.g. Terquem et al., 1999). To maintain equilibrium with the binary torques, the disk needs to be more inclined the further it is from the binary (Capelo et al., 2012).

Other observational trends in protoplanetary disks, as constraints on formation in binary systems, have been noted (Duchêne, 2010). Other constraints have come from Spitzer observations of close binary systems (Matranga et al., 2010).

**Circumbinary debris disks** A number of circumbinary debris disks (§10.6.3) have also been found to be co-planar (Watson et al., 2011; Kennedy et al., 2012b; Greaves et al., 2014), but some misaligned disks exist, e.g. 99 Her (Kennedy et al., 2012a).

## 10.13 Population synthesis

### 10.13.1 Objectives

Predicting the properties of individual planets, whether solar system planets or exoplanets, is a necessary but insufficient condition for validating models of exoplanet formation and evolution. The number of model parameters is large, and they are potentially only poorly constrained by the properties of either a single system, or a small number of systems. But the large number of exoplanets now known also allows their principal properties to be characterised through methods such as principal component or hierarchical clustering analyses, providing possibilities for their taxonomic classification (e.g. Marchi, 2007; Plávalová, 2012).

In the *population synthesis* approach, Monte Carlo models are used to establish the properties of an ensemble of hypothetical planetary systems. Various combinations of plausible initial conditions can be combined with a realistic probability of occurrence to predict the final outcome of the formation process, along with their accompanying probabilities. These can then be compared with the observed planetary population in order

to verify that the most important statistical properties are reproduced, and furthermore to constrain formation models, and to establish probability distributions for the most important initial conditions.

Such an approach forms the basis of deterministic models of planet formation using the statistical properties of orbits, masses and metallicities, and providing constraints on formation models including embryo coagulation and type I migration (Ida & Lin, 2004a,b, 2005b, 2008a,b, 2010; Ida et al., 2013). It has also been used in the assessment of silicon enrichment (Robinson et al., 2006a), and other similar analyses of planetary radii, masses and orbital distance (e.g. Kornet & Wolf, 2006; Thommes et al., 2008b; Broeg, 2009).

Population synthesis models can also be used to make predictions about individual planets or system architectures that have not yet been observed, either because they are created only rarely, or because observational accuracies are so far insufficient to detect them.

### 10.13.2 Observational constraints

A substantial range of observational constraints can now be applied to population synthesis models. Amongst these are dependence on stellar (including spectral) type (§8.5), constraints on orbits, including eccentricities both from radial velocity (§2.10.4) and transit (including Kepler) measurements (§6.26.2), constraints on mass distributions and the mass–radius relation (§6.27), the occurrence and mass distributions of close-in super-Earths, Neptunes and Jupiters (e.g. Howard et al., 2010b; Benítez-Llambay et al., 2011), the statistics of multi-planet systems (§6.30) and mutual orbit inclinations (§6.30.5), and the occurrence around binary and multiple star systems (§10.12).

**Planetary mass function** Establishing fundamental properties of the exoplanet population, such as the fraction of stars in the Galaxy with planetary systems, or the frequency of planets of a given mass in the solar neighbourhood, requires knowledge of the underlying *planetary mass function* in terms of stellar mass  $M_\star$ , metallicity  $Z$ , age  $\tau$ , and spin rate  $\Omega$  (although  $\Omega$  is, typically, itself a function of  $M_\star$  and  $\tau$ ; see §8.2.6).

Dominik (2011) argued that all population statistics can be derived from three fundamental functions, namely the differential stellar mass function  $\xi(M_\star, Z, \tau, \Omega)$ , the fraction of stars with planetary systems  $f_p(M_\star, Z, \tau, \Omega)$ , and the differential mass–radius–orbit function  $\varphi(M_p, R_p, a, e; M_\star, Z, \tau, \Omega)$ .

The mass function for planetary systems around stars with  $(M_\star, Z, \tau, \Omega)$  is then given by

$$\Phi(M_p; M_\star, Z, \tau, \Omega) = \int \varphi(M_p, R_p, a, e; M_\star, Z, \tau, \Omega) \times d[\log(R_p/R_\oplus)] d[\log(a/a_\oplus)] de. \quad (10.84)$$

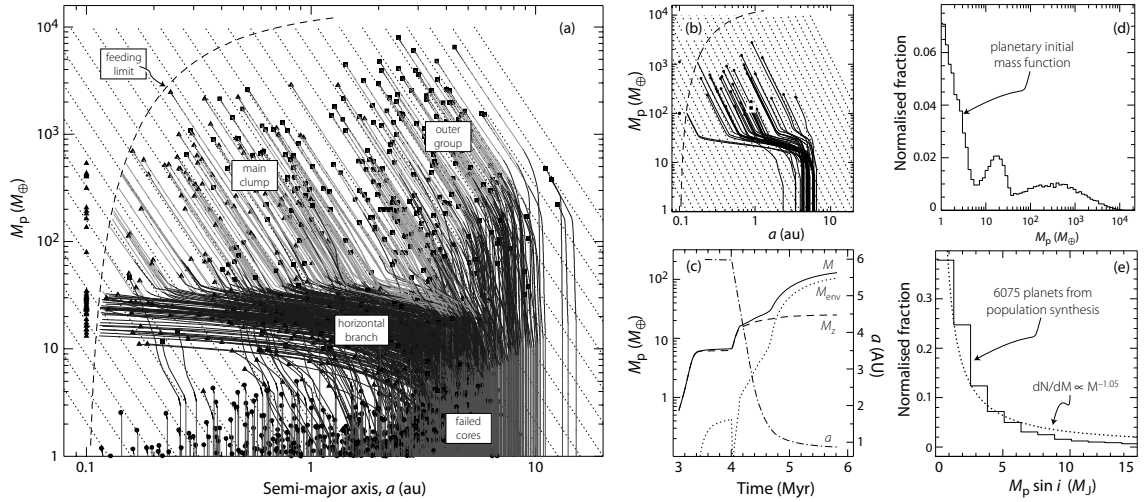


Figure 10.51: Population synthesis model results: (a) formation tracks in the  $(M_p, a)$  plane for 1500 Monte Carlo runs. Large black symbols show final planet positions, where growth and migration stop. Planets reaching the ‘feeding limit’ are set arbitrarily to a final value  $a = 0.1$  au. Short dashed lines have a slope of  $-\pi$ . Four main groupings are indicated (colour-coded by migration mode in the original). Small black dots, plotted on the tracks every 0.2 Myr, indicate each planet’s temporal evolution; (b–c) formation tracks for a subset of planets passing through the ‘horizontal branch’ to become members of the ‘main clump’. The typical embryo highlighted in (b) as a black-on-white square, whose temporal evolution is shown in (c), eventually leads to a Saturn-mass planet at  $a = 0.9$  au. In (c), curves are labeled (left ordinate) with total mass  $M$ , mass of accreted solids  $M_Z$ , envelope mass  $M_{\text{env}}$ , and (right ordinate) semi-major axis  $a$ ; (d) planetary initial mass function, corresponding to the moment in time when the gaseous protoplanetary disk disappears; (e) histogram of the predicted  $M_p \sin i$  for the 6075 detectable simulated planets compared to the observationally inferred  $dN/dM \propto M^{-1.05}$  power law of Marcy et al. (2005a). From Mordasini et al. (2009a, Figures 8 and 11) and Mordasini et al. (2009b, Figures 3 and 5), reproduced with permission © ESO.

The average number of planets in such a system is

$$n_p(M_\star, Z, \tau, \Omega) = \int \Phi(M_p) d[\log(M_p/M_\oplus)]. \quad (10.85)$$

The number density of planets for a stellar population is

$$N_p = \int f_p(M_\star, Z, \tau, \Omega) \xi(M_\star, Z, \tau, \Omega) n_p(M_\star, Z, \tau, \Omega) \times p_Z(Z) dZ p_\tau(\tau) d\tau p_\Omega(\Omega) d\Omega d[\log(M/M_\star)]. \quad (10.86)$$

The population-integrated planetary mass–radius–orbit function is then

$$\psi(M_p, R_p, a, e) = \int f_p(M_\star, Z, \tau, \Omega) \xi(M_\star, Z, \tau, \Omega) \times \varphi(M_p, R_p, a, e; M_\star, Z, \tau, \Omega) \times p_Z(Z) dZ p_\tau(\tau) d\tau p_\Omega(\Omega) d\Omega d[\log(M_\star/M_\odot)], \quad (10.87)$$

with a corresponding planetary mass function

$$\Psi(M_p) = \int \psi d[\log(R_p/R_\oplus)] d[\log(a/a_\oplus)] de. \quad (10.88)$$

The number density of planets is given by

$$N_p = \int \Psi(M_p) d[\log(M_p/M_\oplus)]. \quad (10.89)$$

In principle, the fragmentation of a planetary system into  $k$  planetary bodies gives an infinite number

of multiplicity indices  $\zeta_k$  that correspond to the fraction of planetary systems with exactly  $k$  planets, as well as respective specific mass–radius–orbit functions  $\hat{\varphi}_k(M_p, R_p, a, e; M_\star, Z, \tau, \Omega)$ . Adopting a functional dependence on  $k$  would allow for a description with a finite number of parameters. Quantifying the occurrence of single- and multiple-planet systems also requires excluding the presence of further planets.

Dominik (2011) argued that while current exoplanet samples give first insights into population statistics, a more complete picture will require samples 2–4 orders of magnitude larger, notwithstanding those discovered with Kepler. Surveys with both a high detection rate, and also well-defined detection criteria, will be necessary.

Various attempts to reconcile statistical results from radial velocity, transit, and microlensing surveys, are the first steps in this direction, with the analysis of Clanton & Gaudi (2016) demonstrating powerful constraints from a combination of microlensing, radial velocity, and direct imaging surveys of large-separation ( $\geq 2$  au) planets around single M stars (§5.10.2 and Equation 5.51).

### 10.13.3 Monte Carlo models

Population synthesis studies based on the ‘Bern’ planet formation model take into account, in a self-consistent manner, planetary growth through core accretion

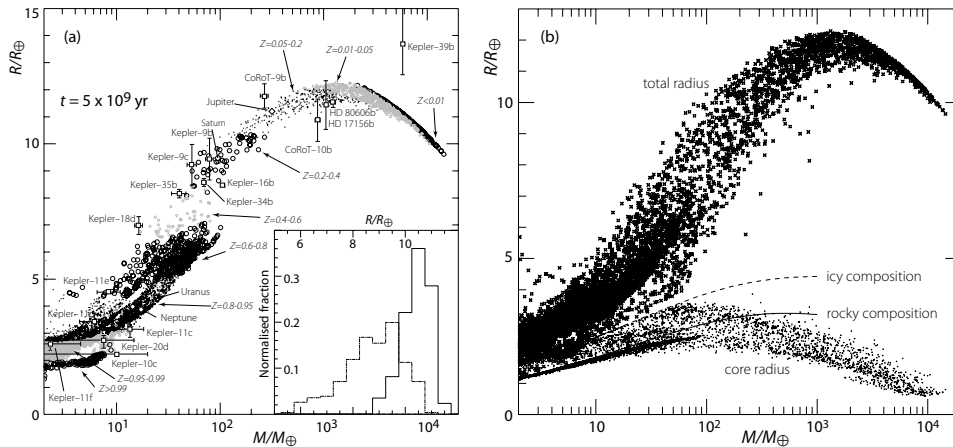


Figure 10.52: Population synthesis model results: (a) mass–radius relation for planets with a final semi-major axis  $a < 1$  au. Planets with known  $M_p$  and  $R_p$ , and with  $a > 0.1$  au, are shown. Arrowed regions (colour-coded in the original) show the fraction of heavy elements  $Z = M_Z / M_p$ . Inset: distribution of  $R_p$  for  $M_p = 100 - 300 M_\oplus$  for a population of age 5 Gyr, divided into  $a < 1$  au (solid line), and  $a > 1$  au (dashed–dotted line and shaded). (b) total radius (larger symbols) and core radius (smaller symbol) as a function of mass for  $M > 2 M_\oplus$  at 5 Gyr. The dashed line is the mass–radius relation for solid planets with an icy composition (roughly solar beyond the iceline with 75% ice, 17% silicates and 8% iron). The solid line is for solid planets with an Earth-like rocky composition (2:1 silicate-to-iron ratio). From Mordasini et al. (2012b, Figures 13 and 16), reproduced with permission © ESO.

(§10.5.1) and type I and type II migration (§10.10.2) in an evolving protoplanetary disk of gas and dust (Alibert et al., 2005a; Benz et al., 2008; Mordasini et al., 2009a,b; Alibert et al., 2011; Mordasini et al., 2012a, 2015).

Their population synthesis modeling initially used four Monte Carlo variables to describe a range of initial conditions: the initial dust-to-gas ratio of the protoplanetary disk (ranging between 0.013–0.13), the initial gas surface density  $\Sigma_0$  at 5.2 au ( $500 - 10^4 \text{ kg m}^{-2}$ ), the photoevaporation rate ( $5 \times 10^{-10} - 3 \times 10^{-8} M_\odot \text{ yr}^{-1}$ ), and the initial semi-major axis of a seed embryo within the disk (0.1–20 au). Each of these is accompanied by corresponding probability distributions. The properties of the resulting synthetic planet population are then characterised, for example, as a function of stellar mass and metallicity, as well as planetary mass, orbit, composition, radius and equilibrium temperature.

The first versions of these models (pre-2010) were tuned to match the distribution of giant planets detected by radial velocity by adjustments to the rate of type I migration. Although the simulations predicted that planet occurrence rises with decreasing planet mass, most of the low-mass planets resided in orbits near or beyond the ice line at  $\sim 2\text{--}3$  au, in contrast to the observed distribution of close-in planets,  $P < 50$  d (Howard et al., 2010b). The Kepler results, post-2011, showed that many planets populate a region sparsely populated by the original models ( $M \sin i \sim 1 - 20 M_\oplus$  and  $a \lesssim 1$  au), and with a planet radius distribution that rises steeply with decreasing planet size (Howard et al., 2012b).

Later model developments have included non-

isothermal treatment of the disk (Paardekooper et al., 2010a), the concurrent formation of many fully-interacting embryos, capture into mean motion resonance, and convergent migration (Mordasini, 2011; Alibert et al., 2013; Benz et al., 2014). As an example, Table 10.1 summarises the model parameters of Mordasini et al. (2012b, their Table 2). Their initial gas surface density profile, of characteristic radius 30 au, is given by (their Equation A1)

$$\Sigma(r, t = 0) = \Sigma_0 \left( \frac{r}{5.2 \text{ au}} \right)^{-0.9} \exp \left[ - \left( \frac{r}{30 \text{ au}} \right)^{1.1} \right]. \quad (10.90)$$

Now providing generally good agreement with observations, these results can explain features such as the lack of high-mass planets orbiting  $0.5 M_\odot$  stars and of short-period planets orbiting  $2 M_\odot$  stars (Alibert et al., 2011), the formation and composition of planets around very low-mass stars (Alibert & Benz, 2017), and are being used to refine models of the processes that take place after the gas clears, such as planet–planet scattering (§10.10.4) and secular and resonant migration (§10.10.2), ultimately aiming to match observed orbital eccentricities and obliquities.

Other statistical modeling along similar lines has also been reported (e.g. Miguel et al., 2011a; Ebisuzaki & Imaeda, 2017). Effects of atmospheric escape are detailed by Jin et al. (2014).

**Sub-populations from evolutionary tracks** Some illustrative results of various Monte Carlo runs from Mordasini et al. (2009a,b) are shown in Figure 10.51a. They identified four main classes of tracks:



- *failed cores*: these low-mass planets occupy the lower-right of the diagram. Growth has ceased since the initial conditions do not allow the formation of more massive planets during the disk's lifetime. Embryos undergo slow type I migration, such that their evolutionary tracks essentially follow constant  $a$ . As expected from the isolation mass, failed cores can reach larger masses at larger distances. Failed-core planets are qualitatively different from terrestrial planets, occupying a similar region of the  $(M_p, a)$  plane, but formed from multiple giant impacts after gas disk dispersal, on much longer time scales;

- *horizontal branch planets*: these were so-designated as a consequence of their morphology in the  $(M_p, a)$  plane (Mordasini et al., 2009a). Type II migration dominates, and on time scales much shorter than the underlying accretion. The transition from type I to type II migration can be accompanied by rapid growth in mass beyond the snow line (§11.2.3), followed by crossing of the snow line on the planet's inward migration (Figure 10.51b,c). They describe this 'horizontal branch' population as 'the conveyor belt by which Neptune-like planets are transported close to the star';

- *main clump planets*: for this population with  $M_p \sim 0.3 - 3M_J$  and  $a \sim 0.3 - 2$  au, the core grows to a size that triggers runaway gas accretion, while also collecting solids as it passes through the horizontal branch region. In this third phase of formation, evolutionary tracks lie on straight lines in the  $(M_p, a)$  plane, with slope  $d \log M_p / d \log a = -\pi$ ;

- *outer group planets*: these are planets with starting positions  $a \gtrsim 4 - 7$  au. The amount of solid material available for accretion is large, and they can grow to a supercritical mass almost *in situ*, without the need to collect additional material by migration. Their evolution tracks are nearly vertical in the  $(M_p, a)$  plane, and they do not pass through the horizontal branch phase, although there is a continuous transition between them and the main clump planets.

**Other diagnostics** In addition to these four sub-populations, Mordasini et al. (2009a) drew attention to the more complex behaviour of type I and type II migration evident from their Monte Carlo modeling. They also identified an absence of massive planets ( $M_p \gtrsim 10M_J$ ) both close to ( $a \lesssim 0.5$  au) and very distant from ( $a \gtrsim 10$  au) the host star, a dearth of planets in the mass range  $30 - 100M_\oplus$ , a number of high-mass, deuterium-burning planets ( $M_p \gtrsim 20M_J$ ), and an absence of Neptune analogues in terms of both  $M_p$  and  $a$  (but with many Neptune-mass planets at smaller separations).

Figure 10.51d shows the derived planetary *initial mass function*, corresponding to the time when the gas disk disperses. Unlike the corresponding stellar power-law distribution, the planetary initial mass function has a complex structure with several minima and maxima.

Table 10.1: Parameters and settings for the population synthesis models of Mordasini et al. (2012b, their Table 2).

Quantity	value
Initial disk profile (their Equation A2)	Equation 10.90
Disk viscosity parameter $\alpha$	$7 \times 10^{-3}$
Inner radius of computational disk	0.1 au
Outer radius of computational disk	free
Gas surface density at inner radius	falls to 0
New photoevaporation model	included
Irradiation for disk temperature profile	included
Rockline	not included
Iceline	included
Embryo starting mass	$0.6M_\oplus$
Core density	variable
Radioactive luminosity	included
Envelope type	primordial $H_2/He$
Accretion shock luminosity treatment	cold accretion
$dI/dr$ in the envelope	0
Grain opacity reduction factor	0.003
Deuterium burning	not included
Envelope evaporation	not included
Type I migration	non-isothermal
Type I migration reduction factor	none
Transition criterion type I to type II	Crida et al. (2006)
Stellar mass	$1M_\odot$
Simulation duration	10 Gyr
Number of embryos per disk	1

Several mechanisms can subsequently modify this initial mass distribution, with the largest changes expected to occur below  $\sim 10 - 20M_\oplus$ .

Figure 10.51e shows the mass distribution of the detectable sub-population of 6075 planets, compared with the power-law fit of Marcy et al. (2005a), showing a broad consistency between the available observational distribution and the population synthesis predictions.

**Mass-radius relation** With the exception of inflated hot Jupiters, which require additional physics (§6.28.4), the forms of the mass-luminosity and mass-radius diagrams are generally well explained by core accretion models, albeit with uncertainties arising from uncertainties in accretional heating (Mordasini et al., 2011a, 2012c,b, 2017).

For example, since low-mass planets cannot bind massive  $H_2/He$  envelopes, while super-critical cores necessarily trigger runaway gas accretion, 'forbidden zones' are found in the mass-radius plane. For a given mass, there is a considerable diversity of radii, mainly due to different bulk compositions, and reflecting different formation histories (Figure 10.52). Further details of the mass-radius relation are given in Section 11.5.

**Mass distribution** The brown dwarf desert is a well-established feature in the mass function of relatively short-period companions to solar-type stars (§2.10.5). It represents a local minimum in the mass function, with the frequency of companions rising toward the stellar regime on the high-mass side, and toward the planetary regime on the low-mass side. The detailed mass distribution of planetary companions associated with any

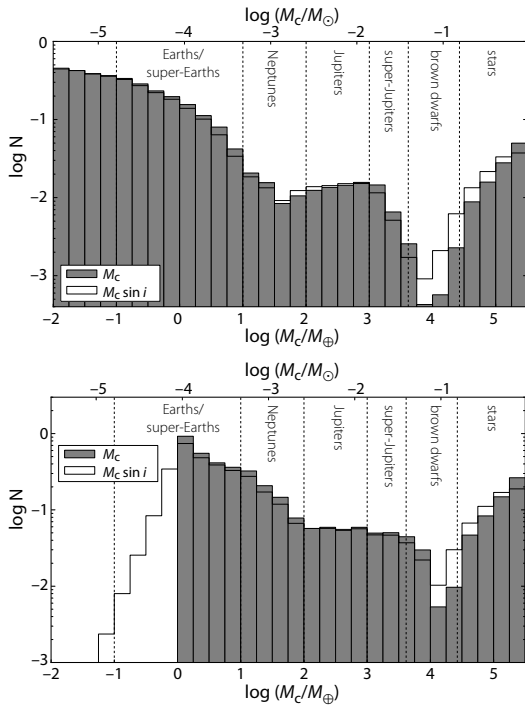


Figure 10.53: Mass distributions of companions around Sun-like stars using planetary companions from the population synthesis models of *Ida & Lin (2008b)*, top, and *Mordasini et al. (2012b)*, bottom. Plots include brown dwarf companions in the D-burning to H-burning mass range. True mass distributions ( $M_c$ ) are shown as filled histograms, while the minimum mass distributions, as measured by radial velocities ( $M_c \sin i$ ), are outlined. Vertical dashed lines divide the plots into various mass regimes. From *Stevens & Gaudi (2013, Figure 5)*, reproduced by permission, Institute of Physics Publishing.

particular stellar spectral type is however rather poorly known. Radial velocity detections yield only the minimum mass of the companion, planets discovered from ground-based transit surveys have severe and difficult-to-quantify selection biases, and mass measurements for most Kepler planets remain unknown.

*Stevens & Gaudi (2013)* estimated the mass distribution of companions around Sun-like stars using the mass functions predicted by the planet formation models of *Ida & Lin (2008b)* and *Mordasini et al. (2012b)*, and various other assumptions about the planet, brown dwarf, and stellar populations. Figure 10.53 shows the resulting distributions of true and minimum masses, divided into several (somewhat arbitrary) regimes.

The distributions all appear qualitatively similar and have several common features: (i) in the stellar regime, the mass function falls toward lower masses as a power-law with a slope  $\alpha \sim 0$ , by design; (ii) there is a local minimum in the brown dwarf regime, with the mass function rising towards lower masses continuing into the planetary regime. In particular, there is a relatively sharp rise for super-Jupiters, with the mass function roughly behaving as a power law with  $\alpha \sim -2$  to  $\alpha \sim -2.5$  over this range; (iii) the mass function for Jupiters is essentially flat in  $\log(M_c)$ , i.e.,  $\alpha \sim -1$ . For lower-mass planets, the mass function again begins to rise, with  $\alpha \sim -1.5$  from the Neptune through the Earth/Super-Earth regime; (iv) the planet formation models predict a peak in the mass function at or below  $1M_{\oplus}$ , with a fall off for less massive companions.

**Solar system analogues** One of the applications for such population synthesis models is to find suitable scenarios and physical parameters of protoplanetary disks which form solar system analogues, in particular the final planet distributions, and in the final surface density, eccentricity and inclination profiles for the planetesimal population. *Ronco et al. (2017)* found that solar system analogues are favoured in massive disks, with low type I migration rates and small planetesimal sizes, and also confirming the picture that rocky planets within their habitable zones are dry when the disks dissipate.

**Tidal downsizing models** Population synthesis models for the tidal downsizing hypothesis of planet formation are details in Section 10.5.2.

**Algorithmic implementation** The Monte Carlo IDL code MESS (Multi-purpose Exoplanet Simulation System), uses discovery results, or formation theories, to build synthetic populations of orbital elements and physical properties (*Bonavita et al., 2011, 2012*).

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# Interiors and atmospheres

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A SIGNIFICANT ADVANCE IN THE KNOWLEDGE of exoplanet interiors and atmospheres was made possible with the discovery of transiting exoplanets. Densities derived from their masses and radii are providing some indications of their interior structure and composition, while optical and infrared transit and eclipse spectroscopy are yielding the first insights into the atmospheric composition, atmospheric dynamics, and thermal transport processes of hot Jupiters. All of this has been substantially facilitated by the knowledge of interiors and atmospheres of the solar system planets and satellites acquired over the last half century.

The insights that can be expected from improved photometric or spectroscopic measurements, for example, with JWST due for launch in 2020, are substantial. For planets inferred to be in the ‘habitable zone’ of their host star, where liquid water is expected to be supported, diagnostics can hope to identify detailed atmospheric compositions, including signatures that may be attributable to primitive or more advanced life forms. These advances are providing a new impetus to searches for life, and even for intelligent life, and the grand question of whether life is extremely common, or extremely rare, elsewhere in the Universe.

## 11.1 Introduction

Physical models of exoplanets span two extreme classes of object, and potentially much in between: the low-mass high-density ‘solid’ planets dominated by metallic cores and silicate-rich and/or ice-rich mantles, and the high-mass low-density gas giants dominated by their massive accreted H/He envelopes.

For the gas-rich giants, models of their interiors and models of their atmospheres are closely connected, and the most recent atmospheric models couple their emergent flux with their assembly by core accretion. Models of their interiors predict bulk properties such as the pressure–temperature relation, and their radii as a function of mass. For close-in, highly irradiated gas giants, the additional external heat source has a significant effect on the pressure–temperature structure of

the outer atmosphere. Combined with inferences on their probable bulk chemical composition, atmospheric models also predict colours and spectral features arising from specific atomic and molecular species.

Interior models of low-mass planets without massive gaseous envelopes aim to determine the mass–radius relation for a given internal composition and, by application of such models, the most likely internal composition given a specific planet’s measured mass and radius. For terrestrial planets, a somewhat distinct problem is establishing the nature of their atmospheres: whether they might have acquired a (modest) gaseous envelope by impact accretion or by outgassing, their likely composition, and whether such an atmosphere might have been retained or eroded over its lifetime.

**Constraints on internal structure** Mass estimates, or lower limits, can be made for exoplanets detected by Doppler measurement, astrometry, microlensing, or timing. Photometric transits also provide an estimate of their radii which, combined with a mass estimate, yield their mean densities. The latter, combined with theoretical models, provides a diagnostic of their composition.

In practice, a unique internal physical and chemical composition cannot be inferred from an object’s mass, volume, and density alone. Neither is it possible to determine directly the presence of a central core, the core’s state (whether liquid or solid), or whether such a core is structurally differentiated or partially mixed with the envelope. But by appeal to the primary constituents observed and inferred in the solar system planets (*viz.* iron, rock, ices, and H/He gas), supported by thermal equilibrium calculations to predict the likely occurrence of particular species, along with their equations of state under assumed internal and external physical conditions, plausible models of their interiors are emerging. Structural inferences are, in turn, being used to provide constraints on their formation.

**Organisation of the treatment** Section 11.2 reviews the likely constituents of planets deduced from considerations of thermodynamic equilibrium, condensation chemistry, and the assumed structure of the proto-

planetary disk out of which planets form. Section 11.3 covers considerations relevant to modeling planet interiors, with some parts focusing on features most relevant to giants or terrestrial planets as appropriate.

The treatment of planet atmospheres is divided into the atmospheres of giant planets (§11.4.1), the principles and application of atmospheric circulation models (§11.4.2), the atmospheres of terrestrial planets (§11.4.3), the atmospheres of ejected planets (§11.4.4), and processes of atmospheric erosion (§11.4.5).

Subsequent sections cover considerations of the mass–radius relation over different regimes (§11.5), the interpretation of transit and eclipse spectra (§11.6), issues of habitability (§11.7), and considerations relevant to the existence and search for life (§11.8).

## 11.2 Planet constituents

This section considers the minerals and compounds that are believed to form from the cooling and accretion of a protoplanetary disk, and the phases and bulk compositions which are likely to be present in the assembled planetary interiors and atmospheres.

### 11.2.1 Gas, rock, and ice

Thermal equilibrium and condensation calculations for approximately solar nebula elemental compositions (§11.2.2) suggest the formation of rather similar minerals and thermal stability sequences over a wide range of total pressures of relevance to the formation of protoplanetary disks ( $P \lesssim 10^2$  Pa).

Thus the most thermally stable solid containing iron is an Fe–Ni metal alloy, for magnesium it is the Mg-silicate forsterite ( $\text{Mg}_2\text{SiO}_4$ ), and for sulphur it is troilite (FeS). As a result of such considerations, it is believed that the planetary constituents forming out of different disks should be comprised of similar oxides, silicates, and sulphides. The relative quantities are determined by the elemental composition of the accretion disk, while their radial distribution is determined by the disk temperature and pressure profiles.

The three principal types of compounds available in accretion disks are loosely referred to as gas, rock (non-volatile condensates), and ice (volatile condensates), and planets form by accreting various amounts of each. Subsequent evolution in temperature and pressure conditions within the planet can modify the phases and redistribute their radial profile through chemical and gravitational differentiation. Though still referred to as comprising ‘ices’ and ‘rocks’, the physical state of these basic constituents in a mature planet may accordingly be very different from that during the accretion phase.

The proportions of gas, rock, and ice determine the planet’s mass and bulk composition (Figure 11.1), while the equations of state determine which phases will be present, along with the size of the resulting planet.

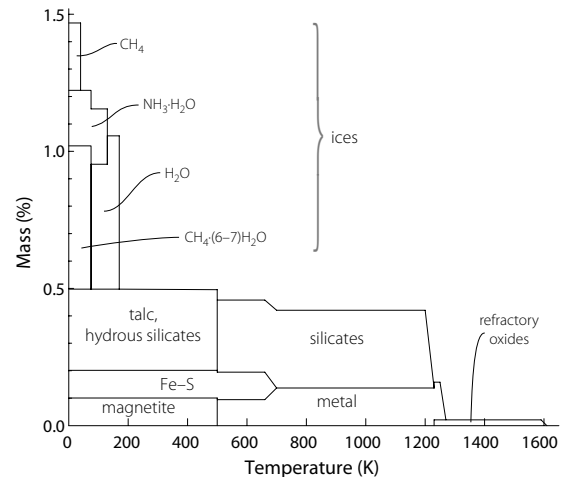


Figure 11.1: The distribution of solid phases (ice and rock) expected in a planetary accretion disk of solar composition at a total pressure of 1 Pa. The calculations assume thermodynamic equilibrium, which is limited by slow gas–gas and gas–solid reactions at low temperatures. From Lodders (2010, Figure 2a).

**Gas** The gas component of gas giants is primarily  $\text{H}_2$  and He, along with whatever species are left over after the rocky and icy condensates have formed (including  $\text{N}_2$  and the noble gases), as well as other secondary photochemical pollutants. H and He comprise  $\sim 98.5\%$  of the mass in the solar nebula, leaving typically  $\sim 1.5\%$  of the total mass bound up in rocks and ices.

**Rock** Geologically, *rock* is defined in the Oxford English Dictionary as ‘Any natural material, hard or soft (e.g. clay), having a distinctive mineral composition’. In the context of exoplanet chemistry, Lodders (2010) suggests as a working definition ‘a component containing the approximate elemental abundances, and consisting of the mineral phases, that are observed in undifferentiated meteorites called chondrites’.

All rocky compounds are relatively refractory, and require high temperatures for evaporation, and condense out of a gas of solar system composition at relatively high temperatures. Being the last material to evaporate, and the first to condense, rock is therefore always expected to be present amongst solids in an accretion disk. By analogy with the solar system abundances, the amount of rocky material is expected to be  $\sim 0.5\%$  of all mass in an accretion disk.

Major minerals commonly encountered in planetary science are listed in Table 11.1. This includes elements like Si, Mg, Ca, Al, and Ti that form oxides and silicates, as well as Fe–Ni metal alloys and FeS. Lodders (2010) gives further details of the expected percentages of various rocky and icy substances under equilibrium and non-equilibrium conditions, and of expected condensates and gases in a solar composition gas giant planet.

Table 11.1: Typical minerals (rocks) made of the more abundant elements. From Lodders (2010, Table 1.1).

Mineral group	Endmember	Formula
Olivine (Mg,Fe) <sub>2</sub> SiO <sub>4</sub>	Forsterite	Mg <sub>2</sub> SiO <sub>4</sub>
	Fayalite	Fe <sub>2</sub> SiO <sub>4</sub>
Pyroxene (Mg,Fe,Ca)SiO <sub>3</sub>	Enstatite	MgSiO <sub>3</sub>
	Ferrosilite	FeSiO <sub>3</sub>
	Wollastonite	CaSiO <sub>3</sub>
Feldspar	Anorthite	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub>
	Albite	NaAlSi <sub>3</sub> O <sub>8</sub>
	Orthoclase	KAlSi <sub>3</sub> O <sub>8</sub>
Metal alloys	Iron-nickel	FeNi
Sulphides	Troilite	FeS
	Pyrrhotite	Fe <sub>1-x</sub> S
Oxides	Magnetite	Fe <sub>3</sub> O <sub>4</sub>
Hydrous silicates	Talc	Mg <sub>3</sub> (Si <sub>4</sub> O <sub>10</sub> )(OH) <sub>2</sub>

Olivine is one of the most common minerals in Earth's crust and upper mantle and, also found in meteorites, the Moon, and Mars, is frequently taken as representative of generic 'rock'. It exists as a solid-solution series, (Mg,Fe)<sub>2</sub>SiO<sub>4</sub>, ranging from the Mg-rich end-member forsterite, Mg<sub>2</sub>SiO<sub>4</sub> ( $\rho = 3.2$ ), to the Fe-rich end-member fayalite, Fe<sub>2</sub>SiO<sub>4</sub> ( $\rho = 4.4$ ). Phase transitions to high-pressure polymorphs occur at  $P \gtrsim 10 - 15$  GPa, depending on temperature and Fe content. Corresponding to depths of 400–500 km on Earth, this yields distinctive changes in seismic records, and marks the transition from upper to lower mantle (Deer et al., 1996).

**Ice** In common usage, the word 'ice' portrays *water* in its cold and solid state. None of these three characteristics are necessarily implied when used in the context of exoplanets. Thus, the solid phases of H<sub>2</sub>O are termed 'ice' even though, at sufficiently high pressure, various solid phases of H<sub>2</sub>O can exist at  $T \gg 273$  K (§11.3.8).

Furthermore in planetary science, volatiles with a melting point between ~100–200 K are commonly referred to as 'ices', even when in a hot and/or liquid form. In this context, ice encompasses various substances containing C, N, and O. Water ice is the most important, in part because O is the third most abundant element in the solar system, but also because it condenses at the highest temperature. Other possibly abundant ices are CH<sub>4</sub>, CO, CO<sub>2</sub>, N<sub>2</sub>, NH<sub>3</sub>, and NH<sub>3</sub>·H<sub>2</sub>O.

As for H<sub>2</sub>O, the former four also occur as *clathrates*, in which a lattice of one molecular type traps and contains another (e.g. Johnson et al., 2012c). For water, these are represented by X·nH<sub>2</sub>O, where  $n = 5 - 7$  is the number of H<sub>2</sub>O molecules in a unit structure into which another molecule 'X' can be accommodated.

**Composition of the solar system planets** Four main compositional types are observed for planets and dwarf planets in the solar system (Figure 11.2).

Terrestrial-type composition, mainly comprising rocky materials (metals and silicates) are represented by

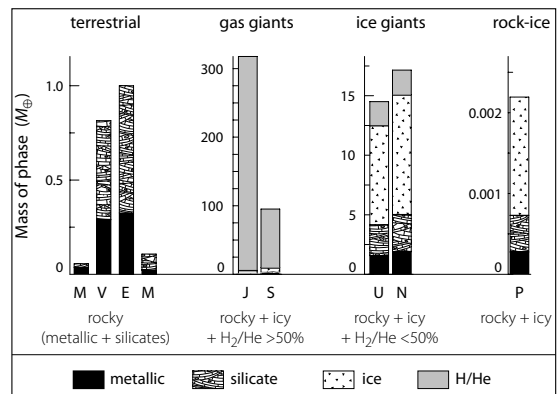


Figure 11.2: Classification of solar system bodies into four compositional types, represented by the terrestrial planets (Mercury, Venus, Earth, Mars), the gas-rich giant planets (Jupiter, Saturn), the ice giants (Uranus, Neptune), and the dwarf planets (typified by Pluto). After Lodders (2010, Figure 1).

Mercury, Venus, Earth and Mars, as well as Ceres and other asteroids. Atmospheres, when present, represent a marginal contribution to their total mass.

In the gas-rich giant planets, Jupiter and Saturn, H and He dominate, and their overall elemental composition is closest to that of the Sun.

Uranus and Neptune accreted only some 10–20% of their mass as H and He gas, leaving them as 'gas-poor' giants, or ice giants.

Bodies composed predominantly of rock and ice are of relatively low mass in the solar system. They are represented by the IAU-designated dwarf planets (such as Pluto, Eris, and Haumea), with some of the asteroids in the outer asteroid belt, and most objects beyond Neptune, likely to belong to the class. Tenuous atmospheres of icy evaporates may exist for the more massive. More massive exoplanets of similar composition, 'ocean planets', (§11.3.8) have been hypothesised.

Further details of the inferred solar nebula abundances are given in Section 12.1.3, and a summary of the present chemical inventory in the box, page 652.

### 11.2.2 Composition and condensation

Details of chemical composition as a function of temperature and pressure are important considerations in many areas of planet formation and evolution, amongst them: (a) in the composition of the solar nebula as a starting point for formation models (§12.1.3); (b) for the detailed chemical studies of dust agglomeration during the earliest phases of planet formation (§10.4.1); (c) for interpreting the qualitative differences of accretion processes within and beyond the snow line (§11.2.3); (d) for modeling the interiors and bulk properties of both giant planets and of Earths and super-Earths (§11.3); (e) for modeling the atmospheres of the gas giants formed by

accretion (§11.4.1), and of terrestrial planets formed by outgassing (§11.4.3); and (f) in interpreting the photospheres of exoplanet host stars, for example, for evidence of accreted material (§8.4.3). These considerations fall within the field of *cosmochemistry*, the study of the chemical composition of the Universe and the processes that produced them (e.g. McSween & Huss, 2010).

Assuming adequate time for the relevant chemical reactions to reach equilibrium, a gas starting out with some initial elemental composition, at a specified temperature (and to a less sensitive degree, pressure), is transformed into a thermodynamically stable mix of elements and compounds in their various permitted elemental, mineralogical, gas, or ice forms. Thermochemical equilibrium calculations can predict the gas phase, gas–grain, and solid phase reactions which occur as a function of pressure and temperature, thereby estimating which gases form, which elements or compounds condense, and in what proportions.

The condensation temperatures of the constituents of a gas of solar composition are widely used as a diagnostic of chemical fractionation in various branches of astronomy, planetary science, and meteoritics. Early thermochemical computations for gas chemistry in the Sun and in cool stars, taking condensation into account, were made by Wildt (1933) and Russell (1934).

Subsequently, numerous studies were dedicated to establishing and refining volatility trends, which are determined by the condensation temperature of each element and its compounds (e.g. Lord, 1965; Larimer, 1967; Grossman, 1972; Grossman & Larimer, 1974; Boynton, 1975; Wai & Wasson, 1977, 1979; Sears, 1978; Fegley & Lewis, 1980; Saxena & Eriksson, 1983; Fegley & Palme, 1985; Kornacki & Fegley, 1986; Palme & Fegley, 1990; Ebel & Grossman, 2000; Gail, 2002, 2004; Lodders, 2003).

**Condensates and condensation temperature** Given a starting prescription of elemental abundances, the resulting composition and condensation fraction can be predicted thermodynamically. The procedure is general, but in the present context can be used, for example, to estimate the composition, in elements and compounds, solids and gases, of the solar nebula.

The following description, based on Lodders (2003), outlines how such constituents can be inferred from the initial elemental abundances. Gail (2002, 2004) reports a similar series of large-scale simulations predicting the abundance of minerals formed in the early solar system, and the most important dust components.

Thermodynamically, the condensation temperature of each specific constituent is determined by the total gas pressure, the elemental abundances that determine the partial pressures, the distribution of an element between different gases and condensates, and the vapour pressure of the element. Condensation temperatures of relevance to the solar system, including those deter-

mined by Lodders (2003) and the numerous previous works cited above, are typically calculated at a total pressure of 10 Pa ( $10^{-4}$  bar), which is considered to be representative of the total pressure near 1 au in the original solar nebula (Fegley, 2000).

In the approach described by Lodders (2003), the numerical code CONDOR (Lodders & Fegley, 1993; Fegley & Lodders, 1994) is used to determine the chemical equilibrium condensation temperatures. It simultaneously solves for the mass balance and chemical equilibrium for 2000 gases (including molecules, radicals, atoms, and ions) and 1600 condensates of all naturally occurring elements. The underlying physics can be conceptualised in two steps, which are in practice coupled and solved iteratively.

In the first step, the abundances of all 2000 gases accounted for in the code are determined as follows, taking Al as an example (Lodders, 2003, section 3.1). For a total abundance in all forms,  $n(\text{Al})$ , the total mole fraction is

$$X_{\Sigma\text{Al}} = \frac{n(\text{Al})}{n(\text{H} + \text{H}_2 + \text{He} + \dots)}, \quad (11.1)$$

where the denominator is the sum of the dominant H, He, and all other gas abundances, with the temperature-dependent equilibrium ratios of H/H<sub>2</sub> (and others) taken into account. Multiplying by the total pressure gives the pressure of Al in all forms, which is equal to the partial pressure sum for Al. This is expressed as

$$P_{\Sigma\text{Al}} = a_{\text{Al}} [K_{\text{Al}} + K_{\text{AlO}} f_{\text{O}_2}^{0.5} + K_{\text{AlOH}} (f_{\text{O}_2} f_{\text{H}_2})^{0.5} + \dots], \quad (11.2)$$

where the  $K_i$  are the equilibrium constants appropriate for forming the relevant gases from the constituent elements in their reference states. The *thermodynamic activity coefficient*,  $a$ , and the *fugacity* of each of the other gases combining with the primary element,  $f$ , account for deviations from ideal thermodynamic behaviour in the specified interactions. Analogous forms are written for each element in the code, with the appropriate  $K_i$  given in the thermodynamic literature, notably the NIST–JANAF thermochemical tables (Chase, 1998).

Equation 11.2 shows that the chemistry of the elements is evidently interdependent. The mass balance equations from the set of coupled, non-linear equations are therefore solved iteratively. An initial estimate can be used for the thermodynamic activity or fugacity of each element, but this can be optimised if the major gas for each element is known. The solution gives the abundance of all resulting gases, along with the thermodynamic activity or fugacity for each combination.

In the second step, condensate stabilities are computed considering the compounds which can be formed from the elements in their respective reference states. For example, the condensation of corundum (Al<sub>2</sub>O<sub>3</sub>),

**Refractory and volatile elements:** condensation temperatures give the volatility groupings for the elements. Lodders (2003) subdivides the 50% condensation temperatures, for solar system abundances at 10 Pa, as:

- ultra-refractory,  $T > 1650$  K: the metals Os, Re, W; the lithophiles Al, Hf, Sc, Th, Y, Zr; and the heavy rare earth elements Gd, Tb, Dy, Ho, Er, Tm, Lu;
- highly refractory, 1650–1500 K: the metals Ir, Mo, Ru; the lithophiles Ca, Nb, Ta, Ti, U; and the light rare earth elements La, Pr, Nd, Sm;
- refractory, 1500–1360 K: the metals Pt, Rh; the lithophiles Ba, Be, Ce, Sr, V, Yb;
- the common elements, 1360–1290 K: Mg, Si, Fe; also the metals Co, Cr, Ni, Pd; and the lithophile Eu;
- moderately volatile, 1290–704 K: the siderophiles Ag, As, Au, Bi, Cu, Ga, Ge, P, Pb, Sb, Te; lithophiles Cs, B, K, Li, Na, Mn, Rb, Zn; the halogens Cl, F;
- volatile, 704–371 K: the chalcophiles Cd, In, S, Se, Te; the siderophile Sn; the halogens Br, I;
- highly volatile,  $< 371$  K (if at all): C, N, O; noble gases; Hg.

The more abundant rock-forming elements are: (highly) refractory (Ca, Al, Ti); common (Fe, Si, Mg); moderately volatile (P); volatile (S); and highly volatile (H, C, N, O).

described by the reaction  $2\text{Al (gas)} + 1.5\text{O}_2\text{ (gas)} = \text{Al}_2\text{O}_3\text{ (solid)}$ , occurs when the thermodynamic activity of  $\text{Al}_2\text{O}_3$  reaches unity. This is calculated from

$$a_{\text{Al}_2\text{O}_3} = a_{\text{Al}}^2 f_{\text{O}_2}^{1.5} K_{\text{Al}_2\text{O}_3}, \quad (11.3)$$

where  $K_{\text{Al}_2\text{O}_3}$  is the temperature-dependent equilibrium constant for corundum, and  $a$  and  $f$  are taken from the gas-phase equilibrium calculations.

At the *appearance condensation temperature* at which the thermodynamic activity of a pure phase (e.g. Fe-metal, FeS, or  $\text{Al}_2\text{O}_3$ ) reaches unity, the compound or element begins to condense from the gas phase. The gas phase abundance is thereby reduced by the fraction condensed. The activities of all possible condensates are computed similarly. The gas-phase and gas-solid chemical equilibria are coupled and solved iteratively.

**Minor and trace elements** The condensation temperatures of minor and trace elements that do not condense as pure phases are computed differently. Many condense by forming (solid) solutions with host phases made of major elements. An understanding of host phases for trace elements is constrained observationally by elemental analyses of minerals in meteorites, and further guided by the geochemical Goldschmidt classifiers denoting preferred host phases (§10.4.7).

The formation of solid solutions starts when a host phase begins to condense, and when the minor and trace elements have the same condensation temperatures as the host phase. The 50% condensation temperature, at which half the element is in the gas phase and the other half is combined into condensates, provides a more robust indication of the extent of condensation or volatility of minor and trace elements.

Table 11.2: A selection of illustrative condensation temperatures, for solar nebula composition, and a total pressure of 10 Pa. From Lodders (2003, Table 7).

Mineral	Name	T (K)
$\text{Al}_2\text{O}_3$	corundum	1677
$\text{CaTiO}_3$	perovskite	1593
$\text{MgAl}_2\text{O}_4$	spinel	1397
$\text{CaAl}_2\text{Si}_2\text{O}_8$	anorthite	1387
Fe	Fe alloy	1357
$\text{Mg}_2\text{SiO}_4$	forsterite	1354
$\text{CaMgSi}_2\text{O}_6$	diopside	1347
$\text{MgSiO}_3$	enstatite	1316
FeS	troilite	704
$\text{Fe}_3\text{O}_4$	magnetite	371
$\text{H}_2\text{O}$	water ice	182

Table 11.2 lists a selection of condensation temperatures. Table 11.3 summarises the resulting condensate distributions for three separate abundance distributions, illustrating the sensitivity of the modeled condensates to the initial elemental composition.

As a caveat, chemical reactions proceed at different rates, which generally decrease exponentially with decreasing temperature. In consequence, there may not have been sufficient time for the predicted low-temperature equilibrium chemistry to take place before the local environment cooled significantly, or before the gaseous solar nebula was dispersed (e.g. Fegley, 2000).

**Refractory and volatile elements** Of the numerous results concerning condensation sequences and their interdependencies described by Lodders (2003), the following points are noteworthy in gaining an overview.

Condensation of the major elements (Al, Ca, Mg, Si, Fe) and other important rock-forming elements (Ti, S, P) form the bulk of rocky material, and their condensates serve as host phases for minor and trace elements. Condensation of the three most abundant rock-forming elements, Mg, Si, and Fe (often called the *common elements*; Larimer 1988; Cowley 1995; Taylor 2001), occurs together over a relatively small (100 K) temperature interval. These elements, and their condensation temperatures, are used to define the *refractory elements*, elements condensing at higher temperatures, and the *volatile elements*, those condensing at lower temperatures (see box on page 563). Several ultra-refractory transition elements condense before any major condensates form. The transition metals W, Re, Os, Ir, Mo, Pt, Rh, and Ru condense before iron metal.

Condensation of the highly volatile elements C, N, and O at low temperatures produces the major fraction of solids, as the high-temperature condensates of all other elements (except the noble gases) only make up about one-third of all condensable material. However, the condensation temperatures and types of condensates of C and N, and to some extent of O, are also affected by kinetic effects.

Table 11.3: Condensate distribution from the numerical simulations of Lodders (2003), as given in their Table 11. Values are percent by mass, assuming equilibrium condensation, for three model compositions: (1) their inferred bulk solar system composition representative of the solar nebula, (2) their revised estimate of the solar photospheric composition, and (3) the literature value from Anders & Grevesse (1989).

Condensate	(1)	(2)	(3)
silicates and oxides (a)	0.303	0.269	0.264
metal + FeS (b)	0.186	0.165	0.176
H <sub>2</sub> O ice (c)	0.571	0.506	0.920
CH <sub>4</sub> ice (d)	0.330	0.292	0.408
NH <sub>3</sub> ice (e)	0.097	0.086	0.134
total rock (a+b)	0.489	0.434	0.440
total ices (c+d+e)	0.998	0.884	1.462
total condensates	1.487	1.318	1.903
rock among condensates	32.89	32.89	23.14
ices among condensates	67.11	67.11	76.84
H <sub>2</sub> O ice/rock	1.17	1.17	2.09
total oxygen in rock	22.75	22.75	14.42

Water ice condensation sets the reference temperature for the appearance of volatile ices. Some oxygen removal from the gas has already taken place with the formation of silicates and oxides. About 23% of all oxygen is bound to rocky elements (Al, Ca, Mg, Si, and Ti) before water ice condenses at 182 K.

Condensation of carbon compounds depends on the gas-phase equilibrium between CO and CH<sub>4</sub>



as a function of temperature. Under equilibrium conditions, CO is the major carbon-bearing gas at high temperature, but is replaced by CH<sub>4</sub> gas with decreasing temperature. At 10 Pa, this occurs below 650 K. Pure CH<sub>4</sub> ice then condenses at 41 K.

Nitrogen condensation is tied to the equilibrium



favouring NH<sub>3</sub> gas formation at low temperatures (and high pressures). At 10 Pa, NH<sub>3</sub> is the major nitrogen-bearing gas below 325 K.

More detailed models of the atmospheric chemistry in giant planets are given for C, N, O by Lodders & Fegley (2002); for S, P by Visscher et al. (2006); and for Fe, Mg, Si by Visscher et al. (2010).

### 11.2.3 The snow line

The region in the protoplanetary disk beyond which water ice can be present is referred to as the *snow line* (also as the ‘frost line’ or ‘ice line’; and although strictly a surface). It divides the inner and hotter zone of the protoplanetary disk from the outer, cold, ice-rich region, and is believed to play an important role in the formation and architecture of planetary systems.

H<sub>2</sub>O-ice forms at  $T \lesssim 182$  K (Table 11.2), although this may be modified by effects such as non-equilibrium carbon chemistry (§11.4.1). As evident from Table 11.3, water and other ices increase the surface density of total condensates over that of rocks alone by a factor of 3–4. The mass of the fastest growing planetesimal (the isolation mass) is expected to scale as  $\Sigma^{3/2}$  (Equation 10.18).

Outward gas motion across the snow line then results in the condensation of H<sub>2</sub>O into ice grains, which can collide, stick and grow until they decouple dynamically from the flow. In this way, the snow line defines the inner edge of a cold ‘trap’, in which the density of solids may have been enhanced, speeding the growth of planetesimals and, ultimately, the cores of giant planets (e.g. Jewitt et al., 2007; Marboeuf et al., 2008). Subsequent inward migration may still leave evidence for this preferential formation region (Rice et al., 2013).

**Detailed models** Early models of the evolution of the snow line generally assumed a fully turbulent steady-state accretion disk, including viscous and stellar heating (e.g. Sasselov & Lecar, 2000; Kennedy et al., 2006; Garaud & Lin, 2007; Kennedy & Kenyon, 2008b; Oka et al., 2011). Turbulence is thought to be driven by magnetorotational instability (§10.3.4), and it transports angular momentum outwards allowing accretion on to the central star. These models typically found that during disk evolution the snow line moves inside the orbital radius of Earth (e.g. Davis, 2005; Garaud & Lin, 2007; Oka et al., 2011).

Formation of a relatively water-devoid Earth is problematic in such models (Martin & Livio, 2012; Quintana & Lissauer, 2014). Within the solar system, H<sub>2</sub>O-rich (C-class) asteroids are found predominantly in the outer asteroid belt (Morbidelli et al., 2000), suggesting that the snow line in the solar nebula lay at around 2.7 au (see also box, page 565). This is somewhat larger than predictions based on a minimum-mass disk characterised by conventional opacities and a mass accretion rate of  $10^{-8} M_{\odot} \text{ yr}^{-1}$ , which placed the snow line at 1.6–1.8 au (Lecar et al., 2006). Passive protoplanetary disks appear to have snow lines at radii  $\sim 1$  au, while those for classical T Tauri accreting disks may lie at  $\sim 3$  au (Lecar et al., 2006; Garaud & Lin, 2007).

As a low-mass host star contracts at constant effective temperature during the pre-main sequence phase, the snow line moves broadly inwards, allowing the rapid formation of icy protoplanets that may collide and merge before the star reaches the main sequence (Kennedy et al., 2006, 2007). More detailed models of protostellar disks around T Tauri stars suggest a non-monotonic evolution with time (Garaud & Lin, 2007): evolving from outside 10 au during FU Ori-type outbursts, to 2 au during the quasi-steady accretion phase, to 0.7 au when the accretion rate drops, finally expanding again to beyond 2.2 au during the transition to the debris disk phase. This should have observable consequences for the distribution of H<sub>2</sub>O, and its isotopic composition, within the solar system and beyond (§12.1.4).

Calculations of the snow line location as a function of stellar mass and age (Kennedy & Kenyon, 2008b; Kenyon & Bromley, 2008) showed that stars above  $3M_{\odot}$  evolve quickly to the main sequence, pushing the snow line to 10–15 au before protoplanets form, and presumably restricting the range of disk masses that can form giant planet cores. Its location is further influenced by mass accretion rate and dust size distribution (Mulders et al., 2015a; Zhang & Jin, 2015; Armitage et al., 2016), as well as CNO abundances (Piso et al., 2016).



**The snow line in the solar system:** The snow line in the solar system is the region of the solar nebula where the mid-plane temperature was below the sublimation temperature of water, or more generally (as a function of substance and partial vapour pressure) where volatile compounds (e.g. H<sub>2</sub>O, NH<sub>3</sub>, CH<sub>4</sub>, CO<sub>2</sub>, CO) could condense into solid ice grains (Hayashi, 1981; Martin & Livio, 2012, 2013a, 2014; Marboeuf et al., 2014b,a). Model-dependent temperatures and locations of the H<sub>2</sub>O-ice snow line are variously given, e.g. 170 K at 2.7 au (Hayashi, 1981), 143–150 K at 3.0–3.2 au (Podolak & Zucker, 2004), 1.6–1.8 au (Lecar et al., 2006),  $\geq 3.1$  au (Martin & Livio, 2012),  $\sim 5.7$  au at  $\tau = 7.6 \times 10^5$  yr (Martin & Livio, 2013a), and  $\sim 150$  K for  $\mu\text{m}$ -size grains and  $\sim 200$  K for km-size bodies (D’Angelo & Podolak, 2015).

Observations suggest that the solar nebula’s snow line was located within the asteroid belt, between Mars and Jupiter. The outer asteroids are icy C-class objects (e.g. Abe et al., 2000; Morbidelli et al., 2000), whereas the inner belt is largely devoid of water. This implies that, during planetesimal formation, the snow line was at around 2.7 au (Martin & Livio, 2012). For example, the dwarf planet Ceres,  $a = 2.77$  au, lies close to the lower estimation for the solar nebula’s snow line, and appears to have an icy mantle and perhaps a water ocean below the surface (McCord & Sotin, 2005; Rambaux et al., 2011; O’Brien et al., 2015).

The term is also used, in context, to denote the *present* distance at which H<sub>2</sub>O-ice can be stable, which differs from that in the early solar nebula due to the different opacity and solar flux, and is  $\sim 2.7$  au (Martin & Livio, 2013a).

Observationally, and rather broadly, radial velocity and transit discovery methods are most sensitive to orbits interior to the snow line, whereas microlensing is more sensitive to orbits beyond.

**Effects of a dead zone** Later models of protoplanetary disks include a low turbulence ‘dead zone’ (§10.3.4), which also significantly modifies the location of the snow line (Martin & Livio, 2012). As a function of infall accretion rate, Martin & Livio (2013a, eqn 19) found

$$R_{\text{snow}} \approx 5.73 \left( \frac{M}{M_{\odot}} \right)^{\frac{1}{3}} \left( \frac{\dot{M}}{10^{-8} M_{\odot} \text{ yr}^{-1}} \right)^{\frac{2}{9}} \left( \frac{T_{\text{snow}}}{170 \text{ K}} \right)^{-\frac{4}{5}} \text{ au}, \quad (11.6)$$

a solution holding for the entire disk lifetime, provided that the surface density in the (magnetorotationally-unstable) active surface layers, ionised by cosmic rays or X-rays, satisfies  $\Sigma_{\text{crit}} \lesssim 500 \text{ kg m}^{-2}$ . Once infall accretion drops to a few  $10^{-10} M_{\odot} \text{ yr}^{-1}$ , the disk is dispersed by photoevaporation (§10.3.6).

Applied to the solar system, their model places the snow line at  $\sim 5.7$  au at  $\tau = 7.6 \times 10^5$  yr, corresponding to an infall rate of  $10^{-8} M_{\odot} \text{ yr}^{-1}$ . For an implied photoevaporation rate of  $3.2 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ , this leaves the snow line where it is observed today, at  $\sim 2.7$  au. With inclusion of a dead zone, unlike in the fully turbulent case, the snow line does not pass inside the radius of the Earth, and a water-depleted Earth can be formed (Martin & Livio, 2012, 2013a).

Models of the current location of the CO snow line also support the existence of such dead zones (Martin & Livio, 2014).

**Particle modeling** Beyond the snow line collisional fragmentation may diminish. In addition to more general simulations and experiments of dust coagulation and compression (§10.4.1) specific studies have explored these more favourable conditions for collisional growth (e.g. Aumatell & Wurm, 2011;

Okuzumi et al., 2012; Drazkowska & Alibert, 2017; Liu et al., 2017c; Schoonenberg & Ormel, 2017; Stammler et al., 2017).

Discontinuities in chemical concentrations as a result of the species-dependent snow lines are expected to be diminished by, and perhaps provide a measure of, turbulent diffusion and viscous spreading (Owen, 2014b; Baillié et al., 2015).

Such considerations will determine the possibility of directly imaging the snow line at the time of planet formation with ALMA (e.g. Banzatti et al., 2015; Notsu et al., 2016). Since the CO snow line is difficult to observe directly with CO emission, for example, its location has been inferred in several disks from spatially resolved ALMA observations of DCO<sup>+</sup> and N<sub>2</sub>H<sup>+</sup> (van’t Hoff et al., 2017).

### 11.3 Planet interiors

Various models of the interiors of the solar system planets have been developed over the past 50 years or more, and these have expanded in ever greater detail and complexity to encompass the growing range and diversity of exoplanets. Some models have focused on giant planets with their substantial gaseous envelopes, some on terrestrial planets, and others consider more general mixtures and properties of rock, ice, and gas, over a range of mass or radius, which are applicable to both. Similarly, basic considerations such as equations of state, heat transport and opacities, radiogenic heating, stellar irradiation, and magnetodynamos apply to a greater or lesser extent across all planet and brown dwarf masses and compositions. For the gas giants, neither is there a clear distinction between interior and atmosphere.

This section, accordingly, covers considerations relevant to the understanding and modeling of all planetary interiors, with some parts focusing on features most relevant to giants or terrestrial planets as appropriate. Subsequent sections focus on specific attributes of the atmospheres of giant planets (§11.4.1) and terrestrial planets (§11.4.3).

Amongst the first detailed models of planetary interiors, Zepolsky & Salpeter (1969) determined radii at zero-temperature for bodies composed of H, He, C, Fe, and Mg over the mass range  $0.3M_{\oplus} - 10M_{\oplus}$ . Stevenson (1982a) determined radii for zero-temperature and warm H, H/He, ice, and rock planets over the range  $1 - 1000M_{\oplus}$ . Saumon et al. (1996) determined radii of giant planets with and without cores. Guillot et al. (1996) extended the determinations to include compositions ranging from H/He to rock for giant planets at small orbital distances. Bodenheimer et al. (2003) determined radii for H/He planets with and without cores for a range of orbital separations, including effects of *insolation* (incident solar radiation) from the host star, considered further in Section 11.3.3.

Fortney et al. (2007b) published model radii for planets composed of water ice, rock, and iron. While generally consistent with preceding work in their regions of overlap, they also included mixed compositions, a wide

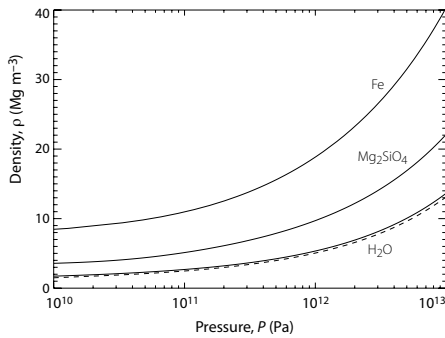


Figure 11.3: Equation of state for iron (Fe), rock ( $\text{Mg}_2\text{SiO}_4$ , olivine/forsterite), and water ice. Solid lines show the zero temperature pressure–density relations. The dashed line for  $\text{H}_2\text{O}$  indicates the effect of thermal corrections. From Fortney et al. (2007b, Figure 1), by permission of IOP Publishing/AAS.

range of core masses, computations over a planet mass range  $0.01M_\oplus - 10M_J$ , and incorporating effects of host star insolation over orbital separations 0.02–10 au.

A review of models of the interiors of giant planets, and outstanding questions, was given by Guillot (2005).

Some of the principles underlying these and other models are described in the following.

### 11.3.1 Equations of state

Many astrophysical problems, exoplanet internal structures amongst them, require detailed knowledge of the physical properties of the constituent matter. An *equation of state* is a thermodynamic relation describing the equilibrium state of matter of a given composition under a specified set of physical conditions. It relates two or more ‘state variables’, i.e. quantities which depend only on the system’s actual state (and not how the body achieved that state) but which are not necessarily independent. State variables include temperature, pressure, volume, density, internal energy, and entropy.

For a star or planet, thermodynamic relations for the pressure  $P(\rho, T)$  and entropy  $S(\rho, T)$  as a function of density  $\rho$  and temperature  $T$  dictate the mechanical and thermal equilibrium respectively. According to context, ‘the’ equation of state for a planet frequently implies the relation  $P(\rho, T)$ , which quantifies the compressibility of the interior, and depends on chemical composition.

Equations of state can be derived for elements, compounds or minerals either experimentally, or by invoking relevant theoretical models over different regions of density and temperature (e.g. Thomas–Fermi–Dirac theory to characterise the interactions between electrons and nuclei, rigid-rotator and harmonic-oscillator methods for molecular rotation and vibration terms). More elaborate models may account for partial dissociation and ionisation caused by both pressure and temperature. Various domains of the equation of state relevant to stars is illustrated in Figure 1 of Pols et al. (1995).

Details of the historical developments and underlying physical techniques in the determination of equations of state are given by Hummer & Mihalas (1988) and Saumon et al. (1995). Tabular equations of state from numerical calculations made at the Lawrence Livermore and Los Alamos National Laboratories, amongst others, have been used extensively in astrophysical applications over many years. The Los Alamos SESAME library, for example, is a compilation of the thermodynamic properties of more than 150 materials including elements, compounds, metals, minerals, polymers and mixtures.

**Examples** The models of Fortney et al. (2007b), for example, use the Los Alamos SESAME 2140 equation of state for Fe (Lyon & Johnson 1992; an alternative is given by Anderson & Ahrens 1994), the Sandia ANEOS models for  $\text{H}_2\text{O}$  and olivine (Thompson, 1990), and the prescriptions given by Saumon et al. (1995) for H and He. H and  $\text{H}_2\text{O}$  are considered further in §11.3.2. For interiors of super-Earths ( $\$11.3.5$ ), details for the rocky cores become more crucial (e.g. Seager et al., 2007; Sotin et al., 2007).

A revised equation of state for H/He mixtures spanning 391 density and temperature conditions typical of giant planet interiors ( $0.2\text{--}9\text{ Mg m}^{-3}$ ,  $1000\text{--}80\,000\text{ K}$ , and He mass fraction  $Y = 0.245$ ) is given by Militzer (2013) and Militzer & Hubbard (2013). Their revised mass–radius relation increases the radius of the hottest planets by  $0.2R_J$ , with possible implications for some discrepant ‘inflated’ hot Jupiters (§6.28.4).

The high-pressure melting curve of Fe, up to 1500 GPa (relevant for terrestrial exoplanet interiors up to  $10M_\oplus$ ), has been determined based on molecular dynamics, and suggests that the Earth may be close to the maximal size for a terrestrial planet to possess a partially molten metallic core, and that the presence of a molten metallic core is less likely for higher masses (Morard et al., 2011). Changing crystalline structures over 0–100 TPa (bcc→hcp→fcc→hcp→bcc), can be calculated quantum mechanically (Cottenier et al., 2011).

Limitations in the current equations of state for the gaseous interiors of giant planets are noted by Guillot (2005, his §2.3).

**Temperature dependence** A non-zero internal temperature modifies the equation of state through the introduction of a thermal pressure term,  $P_{\text{th}}$ , given by

$$P = P_0 + P_{\text{th}}, \quad (11.7)$$

where  $P_0$  is the pressure at  $T = 0\text{ K}$ . Thermal effects are small for high- $Z$  species, with zero- $T$  equations of state believed to be accurate to 1–2% for interior models of Uranus and Neptune (Hubbard & Macfarlane, 1980; Hubbard, 1984). For  $\text{H}_2\text{O}$ , thermal pressure effects amount to ~10%, with models for Uranus and Neptune (Hubbard & Macfarlane, 1980) giving

$$P_{\text{th}} = 3.59 \times 10^6 \rho T, \quad (11.8)$$

with  $P_{\text{th}}$  in Pa,  $\rho$  in  $\text{Mg m}^{-3}$ , and  $T$  in K. The models of Fortney et al. (2007b), for example, accordingly ignore thermal corrections for rock and iron. Within the ice, they assume that the interior temperatures follow the Uranus/Neptune adiabat of Guillot (2005), viz. reaching ~550 K at  $10^8\text{ Pa}$  and 4000 K at  $10^{11}\text{ Pa}$ . They then add the thermal pressure correction of Equation 11.8 at every  $P_0$  (Figure 11.3).

### 11.3.2 Hydrogen and water

**Phase diagram for hydrogen** An understanding of the deep interiors of giant planets comprising H and He has developed over the last three decades (e.g. Stevenson, 1975; Stevenson & Salpeter, 1977b; Hubbard & DeWitt, 1985; Marley & Hubbard, 1988; Saumon et al., 1995; Guillot, 2005; Chabrier et al., 2007).

The behaviour of hydrogen at the relevant temperatures and pressures is complex, but fundamental in predicting densities and heat transport. In the gas giants, molecules, atoms and ions may coexist, in a fluid that is partially degenerate (i.e. the free electron energies are determined by both thermal and quantum effects) and partially coupled through Coulomb interactions.

The pressure–temperature phase diagram of hydrogen (Figure 11.4) shows a number of regions relevant to exoplanet atmospheres (Guillot, 2005): in their relatively cool low-pressure photospheres ( $T \sim 50 - 3000$  K,  $P \sim 10^4 - 10^6$  Pa), hydrogen is in molecular form. Deeper in their interiors, H (and He) becomes progressively fluid. At  $P \geq 10^{11}$  Pa extreme pressures result in ionisation, and the H becomes electrically conductive or ‘metallic’ (Wigner & Huntington, 1935; Loubeyre et al., 1996; Weir et al., 1996; Chabrier et al., 1992; Saumon et al., 2000).

High-pressure laboratory experiments on H and He to further understand the interiors of solar system and other giants have been suggested by Fortney (2007).

**Solidification and solidification time scales** At low temperatures and high pressures, H can solidify (Datchi et al., 2000; Gregoryanz et al., 2003), with three phases recognised (Mao & Hemley, 1994). But as noted by Hubbard (1968), and as evident from Figure 11.4, the interiors of the H/He giants remain fluid, rather than solid, whatever their age: an isolated Jupiter should begin partial solidification only after  $\geq 10^3$  Gyr of cooling.

**Core erosion** Gas giants form by the accretion of H/He gas around a core of rock and ice. In the case of Jupiter and Saturn, it has long been suggested (e.g. Stevenson, 1982a,b, 1985) that some of the dense core material might be dissolved and redistributed in solution with H. Such an erosion of the core would cause it to shrink over the lifetime of the planet, resulting in an *inhomogeneous* distribution of heavy elements in the envelope, with possible consequences for evolutionary models. Specifically, a gradient in concentration of a heavy dissolved component is expected to change the nature of convection in the planet’s interior through *double-diffusive convection*, reducing the efficiency of heat transfer, and altering the planet’s thermal evolution (Guillot et al., 2004; Chabrier & Baraffe, 2007; Leconte & Chabrier, 2012; Mirouh et al., 2012; Soubiran et al., 2017).

Wilson & Militzer (2012b) showed that dissolution of core H<sub>2</sub>O-ice into overlying fluid layers of metallic H is thermodynamically favoured, possibly leading to such core erosion. Wilson & Militzer (2012a) studied rock solubility in fluid H, selecting MgO as a representative example of rocky material, and finding it to be highly soluble for  $T \geq 10000$  K. Similar results were found for SiO<sub>2</sub> (González-Cataldo et al., 2014) which, together with MgO, dissociates from MgSiO<sub>3</sub> under certain conditions (Umamoto et al., 2006), and for Fe for  $T > 2000$  K (Wahl et al., 2013). In turn, a solid-state phase transition for MgO, un-

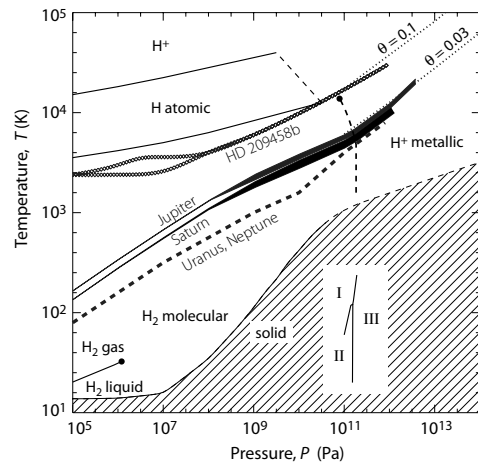


Figure 11.4: Phase diagram for hydrogen. The dashed line near  $10^{11}$  Pa marks the molecular to metallic transition. Hydrogen is solid in the hatched area, with its three phases indicated. Values of the degeneracy parameter  $\theta = T/T_F$  (where  $T_F$  is the Fermi temperature) are shown as dotted lines. Pressure–temperature profiles are shown for Jupiter, Saturn, Uranus, Neptune, and HD 209458 b. From Guillot (2005, Figure 1), by permission, *Annual Reviews* ©2005.

der conditions relevant to super-Earths and giant planets (up to 1 TPa) is described by Coppari et al. (2013).

The models of Leconte & Chabrier (2012) yield values for the metal enrichment of Saturn and Jupiter that are up to 30–60% higher than previously inferred, with smaller central cores (and possibly no core for Jupiter). Their models raise further challenges in determining their heavy material content, a key diagnostic for planet formation theories. Global rotation further affects the dynamics (Moll & Garaud, 2017). In the models of Moll et al. (2017), Jupiter’s entire core could be eroded within 1 Myr. A (very) low core mass has been inferred in the case of HAT-P–13 b (§6.19.4).

In practice, derived core masses also depend on the definition of the core: if defined as the region in which the heavy-element mass fraction is above some limit (say, 0.5), then it can be much more massive ( $\sim 15M_{\oplus}$ ) and more extended (10% of  $R_p$ ) than if defined as the region with 100% heavy elements (Lozovsky et al., 2017).

**Phase diagram for water** The structure and other characteristics of H<sub>2</sub>O (in solid, liquid, or gas form) are dictated by the corresponding phase diagram and associated equations of state (Figure 11.5). Many of its properties, as collated by the International Association for the Properties of Water and Steam (Wagner & Pruß, 2002), are therefore relevant to the predicted characteristics of the ice giants, icy moons, and ‘ocean planets’.

The second most common molecule in the Universe after H<sub>2</sub>, the physical and chemical properties of water are nevertheless extremely complex (e.g. Hobbs, 1974; Brovchenko & Oleinikova, 2008), in large part due to its versatile intra-molecular hydrogen bonding. Chaplin (2010), for example, lists 67 anomalous properties as compared with other liquids.

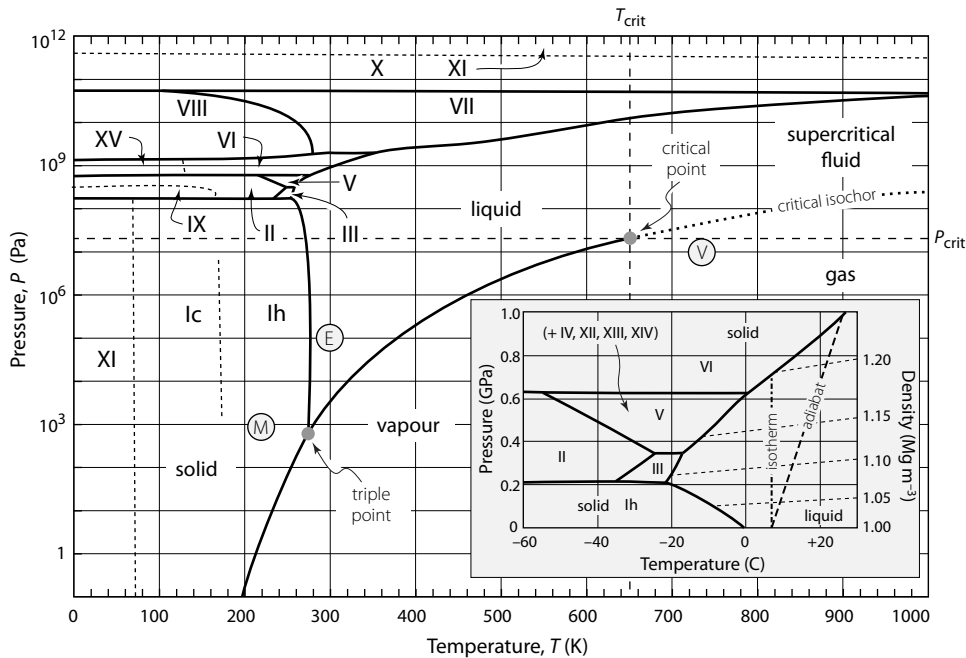


Figure 11.5: Phase diagram for water. Heavy lines indicate boundaries between two phases. The triple point is the intersection of the solid/liquid, liquid/gas, and gas/solid phase boundaries, and where these three phases can accordingly coexist ( $T_{\text{tp}} = 273.16 \text{ K}$ ,  $P_{\text{tp}} = 611.657 \text{ Pa}$ ). The critical point is the location at which the gas–liquid phases merge into a single supercritical fluid ( $T_{\text{crit}} \sim 647 \text{ K}$ ,  $P_{\text{crit}} \sim 22.064 \text{ MPa}$ ). Roman numerals designate the various solid phases. Mean surface conditions are indicated for (M)ars, (E)arth, and (V)enus. Inset: enlargement of the central region, showing isodensity lines for the liquid phase (dashed). The dot-dash (isothermal) and long-dash (adiabatic) lines are relevant to ocean depths (§11.3.8). Adapted from Chaplin (2010).

The *triple point* of water, the temperature and pressure at which the solid, liquid and gas phases<sup>1</sup> coexist in thermodynamic equilibrium, occurs at  $T_{\text{tp}} \equiv 273.16 \text{ K} \equiv 0.01 \text{ C}$  (by definition) and at a partial vapour pressure of  $P_{\text{tp}} = 611.657 \text{ Pa}$  (Guildner et al., 1976). [More generally, triple points occur where any three phase lines join, and  $\text{H}_2\text{O}$  has many other triple points corresponding to its many solid phases].

The *critical point* ( $T_{\text{crit}} \sim 647 \text{ K}$ ,  $P_{\text{crit}} \sim 22.064 \text{ MPa}$ ) occurs at the end of the liquid–gas phase line where the properties of these two phases become indistinguishable. Beyond the critical point, only a single homogeneous supercritical fluid phase exists.

**Polyamorphs and polymorphs** Water has 19 known solid phases (Chaplin, 2010): three non-crystalline *polyamorphs* (LDA, HDA, VHDA, designating low-density, high-density, and very high-density amorphous), and 16 crystalline *polymorphs*, distinguished by their structure, ordering and density. These are designated Ih (hexagonal, the predominant form in the

biosphere), Ic (cubic), and II–XV (variously displaying cubic, hexagonal, monoclinic, orthorhombic, rhombohedral or tetragonal forms, and in which the H-bonding may be ordered or disordered). Ice IV and XII are metastable, with IV, XII–XIV occurring in the phase space of ice V.

Densities are  $\rho < 1 \text{ Mg m}^{-3}$  only for ice Ih/Ic (0.92) and LDA. Densities of other well-characterised phases exceed 1.14, reaching  $2.51 \text{ Mg m}^{-3}$  for ice X.

Ice XI refers to both a low-temperature (ferroelectric) polymorph of ice Ih, but also to a theoretical high-pressure form (also referred to as ice XIII, a name, confusingly, also assigned to another form). The high-pressure phase is expected to be a dense ( $\sim 11 \text{ Mg m}^{-3}$ ) fluid plasma under conditions relevant for Jupiter’s core of  $T \sim 20000 \text{ K}$  and  $P \sim 5 \times 10^{12} \text{ Pa}$ , and possibly superionic within Saturn and Neptune (French et al., 2009).

Other determinations of the phase diagrams of  $\text{H}_2\text{O}$  (and  $\text{NH}_3$ ) of relevance for the middle ice layers of Neptune and Uranus ( $P = 30 - 300 \text{ GPa}$ ,  $T = 300 - 7000 \text{ K}$ ) were reported by Cavazzoni et al. (1999). Melting curves at high pressure have been studied by Datchi et al. (2000), and shock compression results to  $700 \text{ GPa}$  and  $\rho = 3.8 \text{ Mg m}^{-3}$  have been characterised by Knudson et al. (2012).

New and complex properties of water, notably at the more extreme conditions of temperature and pressure, are still being discovered. For example, ice XII was discovered in 1996, ices XIII–XIV in 2006, ice XV in 2009 (Salzmann et al., 2009), and its least dense crystalline form, ice XVI, in 2014. Meanwhile, models of icy exoplanet interiors (e.g. Valencia et al., 2007b) typically take into account at least the high-pressure phases

<sup>1</sup>The terms ‘gas’ and ‘vapour’ are frequently used as synonyms (as here) although, more strictly, vapour is a gaseous substance below  $T_{\text{crit}}$ , and which can therefore be liquefied by pressure alone. ‘Steam’ is commonly used synonymously for water vapour, especially when above the boiling point.

ice VII (Fei et al., 1993; Frank et al., 2004) and ice X (Pruzan et al., 2003; Caracas, 2008; Aarestad et al., 2008).

Although the phase structure may have limited effect on radii (Valencia et al., 2006) it does impose conditions on the compositional phases that are likely to occur towards the planet surface (Zeng & Sasselov, 2014), and on formation processes in the early solar nebula (Ciesla, 2014).

**Clathrates** Clathrate-type entrapment of volatiles (e.g. CH<sub>4</sub>) in an ice envelope, the stability of CH<sub>4</sub>-filled ice Ih, and effects on atmospheric composition, are detailed by Levi et al. (2013).

### 11.3.3 Structural models

The structure and evolution of a spherically symmetric giant planet are considered to be governed by the equations of hydrostatic and thermodynamic equilibrium, and mass and energy conservation. These can be expressed as (e.g. Guillot 2005, equations 1–4)

$$\frac{\partial P}{\partial r} = -\rho g \quad (11.9)$$

$$\frac{\partial T}{\partial r} = \frac{\partial P}{\partial r} \frac{T}{P} \frac{d \ln T}{d \ln P} \quad (11.10)$$

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho \quad (11.11)$$

$$\frac{\partial L}{\partial r} = 4\pi r^2 \rho \left( \dot{\epsilon} - T \frac{\partial S}{\partial t} \right), \quad (11.12)$$

respectively, where  $P$  is the pressure,  $\rho$  the density,  $L$  the intrinsic luminosity,  $S$  the entropy per unit mass, and  $g = GM/r^2$  the gravity.  $\dot{\epsilon}$  accounts for energy produced by nuclear (above  $\sim 13M_J$ ), radiogenic, or tidal heating. Equivalent expressions are given by Fortney et al. (2007b, eqn 3–5). The resulting models of cooling and contracting adiabatic planets, described further by Fortney & Hubbard (2003, 2004), have been applied to evolutionary models of Jupiter and Saturn (Fortney & Hubbard, 2003), cool giant exoplanets (Fortney & Hubbard, 2004), and hot Jupiters (Fortney et al., 2006b).

General models of giant planets assume a core of an unknown mass, comprising an unknown generic combination of iron, refractory material ('rock') and more volatile species ('ices', such as H<sub>2</sub>O, CH<sub>4</sub>, and NH<sub>3</sub>), and a fluid envelope mostly comprising H/He. In contrast to terrestrial planets, effects of viscosity, rotation and magnetic fields are generally neglected. The models of Fortney et al. (2007b) also explicitly ignore tidal heating, the heat content of the core and its unknown heat transport properties (Fortney et al., 2006b), and changes in radius over time for the zones of water/rock/iron (i.e. ignoring  $\partial S/\partial t$  in Equation 11.12).

Helium phase separation would act to increase the radius of cold gas giants, but is considered unlikely to affect irradiated giants within a few au of their host stars (Fortney & Hubbard, 2004).

**Heat transport and opacities** The internal temperature gradient,  $d \ln T/d \ln P$  in Equation 11.10, depends

on the process by which the internal heat is transported from the interior regions to the surface. That (isolated) giant planet interiors are essentially convective, rather than transporting heat by radiation or conduction, follows from the rapid increase in opacity with increasing pressure and temperature (Hubbard et al., 2002).

At  $P \geq 10^5$  Pa and  $T \lesssim 1000$  K, the dominant opacity sources are H<sub>2</sub>O, CH<sub>4</sub>, and collision-induced H<sub>2</sub> absorption (Guillot, 2005; Wordsworth, 2012).

At intermediate temperatures,  $T \sim 1000 - 2000$  K, an effect of decreasing H/He opacity with increasing temperature was predicted by Guillot et al. (1994a,b) which, it was argued, could result in the presence of a radiative shell deep in the interiors of Jupiter, Saturn, and Uranus. This possibility was revised by Guillot et al. (2004) after the identification of additional sources of (Na/K) opacity in brown dwarfs in the spectral regions where H, He, H<sub>2</sub>O, CH<sub>4</sub>, and NH<sub>3</sub> are relatively transparent (Burrows et al., 2000b). These sources are also confirmed in more recent opacity determinations (Freedman et al., 2008).

At  $T \geq 1500 - 2000$  K two additional opacity sources contribute: absorption by H<sub>2</sub><sup>-</sup> and H<sup>-</sup>, and the presence of TiO, which is a strong absorber at visible wavelengths, and which results from the vaporisation of CaTiO<sub>3</sub>.

The thin radiative atmosphere which exists above the otherwise fully convective region controls the ultimate cooling of the giant planet, and hence the contraction of its interior. The fact that giant planet atmospheres have numerous atomic and molecular absorbers (including H<sub>2</sub>O, CH<sub>4</sub>, NH<sub>3</sub>, Na, and K) means that their atmospheres are distinctly non-blackbody (Burrows et al., 1997; Marley et al., 1999; Sudarsky et al., 2000). As a result, self-consistent 'non-grey' atmospheric models must be used to determine  $T_{\text{eff}}$ , and hence the external boundary conditions for the evolutionary models (Baraffe et al., 2003; Marley et al., 2007b).

Equilibrium structure models typically cover a grid of gravities,  $T_{\text{eff}}$ , and incident fluxes. Thus Fortney et al. (2007b) used low-temperature mean opacities (Freedman et al., 2008), on the assumption of solar metallicity atmospheres (Lodders, 2003, §12.1.3). They included the effects of condensation and gravitational settling ('rainout') on the atmospheric composition (Lodders & Fegley, 2002; Lodders, 2003, §11.4.1).

**Cooling rate of Jupiter** For Jupiter, the resulting cooling rate estimated by Hubbard (1977) is  $\Delta T_{\text{eff}} = -6.9 \text{ K Gyr}^{-1}$ .

**Radiogenic heating** Earth's radiogenic heat generation has evolved since its formation (Table 11.4), and the same holds for other planets. Frank et al. (2014) used models of Galactic chemical evolution to predict exoplanet radiogenic heat production as a function of age. They showed that the later a planet forms in Galactic history, the less radiogenic heat it starts out with. At the same time, due to radioactive decay, older planets will

**Opacities:** More than half a century ago, in the context of stellar structure and evolution, Schwarzschild (1958) considered the determination of opacities, quantifying the absorption and scattering of radiation, to be ‘by far the most bothersome factor in the entire theory’. He took account of three processes: photoionisation (bound–free transitions), inverse bremsstrahlung (free–free transitions) and electron scattering. Later work showed that spectral lines (bound–bound transitions) were also significant, eventually leading to the widely-used Los Alamos opacities (Huebner et al., 1977).

By the 1980s, discrepancies between observation and theory, notably for Cepheid pulsations (Simon, 1982) and solar oscillations (Christensen-Dalsgaard et al., 1985), led to the suggestion that those tables were missing important opacity sources. Combined with the need for opacities of low- $Z$  species, this led to the re-examination of stellar opacities by two groups: the Opacity Project (Seaton et al., 1994) and the OPAL group at Livermore (Rogers & Iglesias, 1992). They adopted independent approaches, and both duly reported opacities generally higher than the previous Los Alamos values, reaching factors of 2–3 in stellar envelopes with  $T \sim 10^5 - 10^6$  K. Opacity Project and OPAL opacities are in reasonable agreement (Seaton et al., 1994; Iglesias & Rogers, 1996); and good agreement between OPAL opacities, and those of Alexander & Ferguson (1994) or Kurucz (1991), is also found in the domains where they overlap. Subsequent comparisons have been made using revised Opacity Project data (Badnell et al., 2005). With these new opacities, a number of long-standing problems in stellar evolution have been addressed and, in turn, finer tests of stellar structure have been made possible.

In the present context, and at the temperatures relevant for exoplanets, planetary disks, brown dwarfs, and cool stars, molecular transitions dominate over those of atoms and atomic ions. They dominate the spectral signatures, and provide their major opacities which, in turn, determine their atmospheric structures (e.g. Sharp & Burrows, 2007; Bernath, 2014). Each species may have some  $10^5 - 10^9$  spectral lines, which may be broadened by high-pressures and temperatures. As an example, state-of-the-art ‘hot’ ro-vibrational transitions of  $\text{NH}_3$  comprise more than  $10^9$  lines (Yurchenko et al., 2011).

For these sources, the demand for improved line lists and opacities continues. In their review, Allard et al. (1997) found that the majority of molecular opacities available were based on statistical or other approximate treatments, and gave no case where the available line lists were adequate (although the situation has improved somewhat since). As one example,  $\text{CH}_4$  was detected in HD 189733 b by Swain et al. (2008b), who lacked the data necessary to determine its abundance.

Freedman et al. (2008, 2014) provided some of the most recent tables of mean opacities relevant for giant exoplanet atmospheres. Their earlier results covered three metallicities,  $[\text{M}/\text{H}] = -0.3, 0.0, +0.3$ , and sample a grid of 324 points spanning  $T = 75 - 4000$  K and  $P = 30 - 3 \times 10^7$  Pa. They give both Planck mean opacities, relevant for optically thin regions, and Rosseland mean opacities, most relevant for optically thick regions (Mihalas, 1978). Relevant thermochemical equilibrium abundances were computed with the CONDOR code (§11.2.2). Molecular species, also accounting for relevant isotopes, include  $\text{H}_2\text{O}$  ( $2.9 \times 10^8$  lines),  $\text{CH}_4$  ( $2 \times 10^8$ ),  $\text{NH}_3$  (34 000),  $\text{TiO}$  ( $1.7 \times 10^8$ ),  $\text{VO}$  ( $3.1 \times 10^6$ ),  $\text{CO}$ ,  $\text{H}_2\text{S}$ ,  $\text{PH}_3$ ,  $\text{FeH}$ , and  $\text{CrH}$ . Significant opacity contributions also arise from the alkali atoms Na, K, Cs, Rb, and Li (Burrows et al., 2000b; Allard et al., 2003; Burrows & Volobuyev, 2003). Collision-induced absorption includes interactions between  $\text{H}_2$ – $\text{H}_2$ ,  $\text{H}_2$ –He, and  $\text{H}_2$ –H (Borysow, 2002, and references). Other opacity sources include bound–free absorption by H and  $\text{H}^-$ , free–free absorption by H,  $\text{H}^-$ ,  $\text{H}_2$ , and  $\text{H}_2^-$ , Rayleigh scattering from  $\text{H}_2$ , and Thomson scattering (Lenzuni et al., 1991).

Other relevant line lists include the spectroscopic databases HITRAN (Rothman et al., 2009) and GEISA (Jacquinet-Husson et al., 2011) for molecular transitions at  $\sim 300$  K (appropriate for the solar system planets); the JPL (Pickett et al., 1998) and CDMS (Müller et al., 2005a) databases providing molecular line lists for  $\lambda > 30 \mu\text{m}$ ; HITEMP (Rothman et al., 1995, 2010) for molecular spectra at high temperatures for five species; other lists for a number of molecules (Kurucz, 2011); partial lists of diatomic opacities from UGAMOP (University of Georgia) and RADEN (Moscow State University); and SCAN, for a few diatomic and triatomic molecules (Jorgensen, 1996).

Various relevant cross sections have also been derived empirically, amongst them, for  $\text{CO}_2$  in the ultraviolet (Venot et al., 2013), and for  $\text{CH}_4$  at 300–1400 K in the infrared (Hargreaves et al., 2012).

A specific recent initiative is the ExoMol project, which is generating more complete (high-temperature) spectroscopic transitions for some 30 key molecular species of particular relevance for exoplanets (Tennyson & Yurchenko, 2012, 2015; Tennyson et al., 2016; Tennyson & Yurchenko, 2017). Target environments are broadly divided into hot Jupiters with their reducing or H-rich chemistry (with requirements for  $\text{CH}_4$ ,  $\text{C}_2\text{H}_2$ ,  $\text{C}_2\text{H}_6$ ,  $\text{C}_3\text{H}_8$ ,  $\text{H}_2\text{S}$ , and  $\text{PH}_3$ ), and super-Earths, expected to be oxidising or O-rich (with requirements on  $\text{O}_3$  and, e.g. oxides of nitrogen and sulphur). Their objectives include diatomic molecules (e.g.,  $\text{C}_2$ ,  $\text{O}_2$ ,  $\text{AlO}$ ,  $\text{CaH}$ ,  $\text{FeH}$ ,  $\text{MgH}$ ), triatomics (e.g.,  $\text{C}_3$ ,  $\text{H}_2\text{O}$ ,  $\text{H}_2\text{S}$ ,  $\text{SO}_2$ ), tetraatomics (e.g.,  $\text{HOOH}$ ,  $\text{H}_2\text{CO}$ ,  $\text{PH}_3$ ) and a few larger molecules (notably  $\text{CH}_4$  and  $\text{HNO}_3$ ). Their current compilation, references to their published line lists (currently more than 20 publications), and a list of molecular data available from other sources, is given by Wong et al. (2017). ExoMol employs a mixture of first principles and empirically-tuned quantum mechanical methods to compute comprehensive and very large rotation-vibration (*ro-vibration*) and rotation-vibration-electronic (*ro-vibronic*) line lists. Associated data include energy levels, partition functions, cooling functions and cross sections.

ExoMol line lists are now being used in the modeling of the atmospheres of brown dwarfs (e.g. Cushing et al., 2011; Morley et al., 2014; Canty et al., 2015), and exoplanets (e.g. Beaulieu et al., 2011; Yurchenko et al., 2014; Barman et al., 2015; Mollière et al., 2015; Morley et al., 2015; Tsiaras et al., 2016a).

Convenient access to the most relevant lists is given at [www.exomol.com](http://www.exomol.com), along with procedures to ‘down select’ from the billions of lines to the most important cross sections at any given temperature (Hill et al., 2013; Cubillos, 2017). Other compilations and approximations to dust properties, including opacities and albedos, for particle radii from 0.01–100  $\mu\text{m}$ , over the range  $\lambda = 0.2 - 500 \mu\text{m}$ , have also been presented (Cuzzi et al., 2014; Budaj et al., 2015; Woitke et al., 2016).

In situations exemplified by exoplanet atmospheres, each molecular line is broadened by temperature or Doppler (Gaussian) and pressure (Lorentz) broadening, the convolution yielding the associated *Voigt profile*. A random sampling technique for fast computation of the resulting molecular opacities is given by Min (2017).

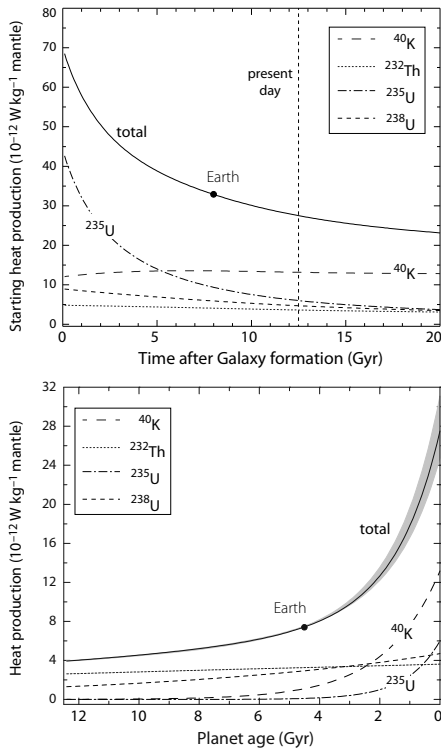


Figure 11.6: Radiogenic heating. Top: initial heat production of  $^{40}\text{K}$ ,  $^{232}\text{Th}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ , and their total in Earth-like mantles versus formation epoch, also showing the starting heat production rate in Earth's mantle. Bottom: current heat production in exoplanets as a function of age. The grey band shows the range of heat production from  $^{40}\text{K}$ , depending on the proportions of primary versus secondary contributions. From Frank et al. (2014, Figures 7 and 10), with permission from Elsevier.

now have lower heat outputs per unit mass than newly-formed planets.

The long half-life of  $^{232}\text{Th}$  means that it continues to provide a small amount of heat even in the oldest planets, while  $^{40}\text{K}$  dominates in the youngest (Figure 11.6). They inferred that younger, hotter rocky planets are more likely to be geologically active, and therefore able to sustain the crustal recycling (and plate tectonics) that may be required for long-term habitability. They concluded that the search for Earth-like planets should focus on stars within  $\sim 1$  Gyr of the Sun's age.

**Stellar irradiation** In addition to internal heat sources (radiogenic or tidal) which change the cooling rate, stellar irradiation further modifies the thermal properties of an otherwise isolated planet atmosphere (§11.4.1), and can contribute to heat flow deeper in their interiors.

Effects of stellar irradiation are particularly significant for hot Jupiters at small orbital separations (Guillot & Showman, 2002; Baraffe et al., 2003; Burrows et al., 2004a; Laughlin et al., 2005c; Arras & Bildsten, 2006; Marley et al., 2007a), but also for older low-mass plan-

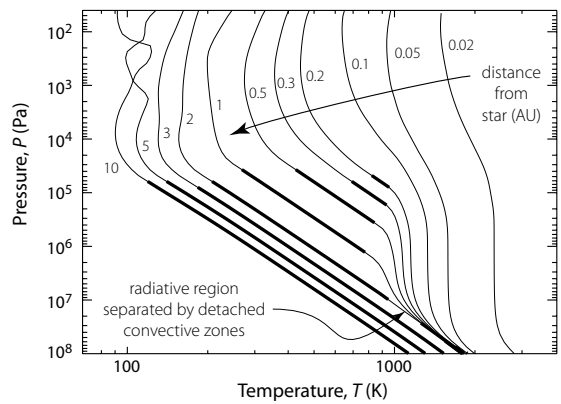


Figure 11.7: Pressure–temperature profiles for Jupiter-like planets of age  $\sim 4.5$  Gyr ( $g = 25 \text{ m s}^{-2}$ ,  $T_{\text{int}} = 100 \text{ K}$ ) from 0.02–10 au from the Sun. Thin lines indicate radiative regions, and thick lines convective regions. At small separations, a radiative region extends deep into the atmosphere, and convection does not begin until  $P > 10^8 \text{ Pa}$ . From Fortney et al. (2007b, Figure 3), by permission of IOP Publishing/AAS.

ets at larger orbital separations for which their diminishing intrinsic effective temperature,  $T_{\text{int}}$ , would otherwise fall below its equilibrium temperature,  $T_{\text{eq}}$ . The latter is itself determined by the incident stellar flux. By definition (Fortney et al., 2007b, eqn 6)

$$T_{\text{eff}}^4 = T_{\text{int}}^4 + T_{\text{eq}}^4. \quad (11.13)$$

For  $T_{\text{int}} \ll T_{\text{eq}}$ , the incident stellar flux dominates, and a more extensive radiative zone develops.

Resulting pressure–temperature profiles for a Jupiter-like planet from 0.02–10 au from the Sun are shown in Figure 11.7. The adopted intrinsic temperature,  $T_{\text{int}} = 100 \text{ K}$ , is close to Jupiter's current value (Table 12.2). Bond albedos range from  $A_{\text{B}} \sim 0.05 - 0.1$  within 0.1 au, to larger values of  $A_{\text{B}} \sim 0.3 - 0.4$  from 1–10 au. At larger separations, cooler temperatures result in the strong alkali metal absorbers Na and K condensing into clouds below the visible atmosphere.

A deep external radiative zone appears in the most highly irradiated models, and for planets at  $< 0.05$  au, convection does not begin until  $P \gtrsim 10^8 \text{ Pa}$ . From 0.1–2 au, the presence of two detached convective zones inhibits heat flow from the central regions, while stellar irradiation over this separation range has roughly the same retarding effect on cooling and contraction, even though the incident fluxes vary by a factor 400.

**Magnetodynamics** In the solar system, magnetic fields and dynamo activities are varied and not well understood in detail (cf. box, page 426). The axial-dipole dominated magnetic fields produced by Earth, Jupiter and Saturn are attributed to 'thick-shell' geometries for the dynamo regions. In contrast, the  $\text{H}_2\text{O}$ -rich giants Uranus and Neptune exhibit non-axisymmetric, non-

dipolar magnetic fields, which are attributed to a dynamo generated in a thin convecting shell of ionically-conductive water phase surrounding a stably stratified layer (Stanley & Bloxham, 2004, 2006). The weak magnetic field of Mercury is difficult to explain by crustal remnant magnetism or Earth-like dynamo mechanisms, and may be explained by Fe ‘snow zones’ midway through the core (Vilim et al., 2010).

**Detailed models** Gaidos et al. (2010) detailed a parametric model of a differentiated rocky planet and its thermal evolution in the presence of a magnetic dynamo like Earth’s (box, page 663). Their model reproduces the established properties of Earth’s interior and magnetic field at the present time, shows that the dynamo shuts down or never operated on Venus, and predicts that rocky planets larger than  $2.5M_{\oplus}$  will not develop inner cores because the net transfer of latent heat upward will suppress convection and a dynamo, while more massive planets can have weak dynamos due to core cooling. They identified two alternative sources of magnetic fields on rocky planets: eddy currents induced in the hot or molten upper layers of planets on very short-period orbits, and dynamos in the ionic conducting layers of ‘ocean’ planets in which ~10% of the mass is in an upper mantle of water or ice. For Earth-mass planets with plate tectonics, magnetodynamo lifetimes are predicted to be of order 8 Gyr (Summeren et al., 2013).

Tian & Stanley (2013) modeled (sub-)Neptune mass planets with four layers: Fe core, silicate layer,  $H_2O$  layer, and H/He envelope, and found that smaller planets and those with a thicker H/He envelopes are likely to be in the regime of a thick-shelled dynamo, and *vice versa*.

Intense stellar irradiation is likely to render hot Jupiter atmospheres electrically conductive through thermal ionisation. Simultaneously, lateral variability in irradiation drives a global circulation with peak wind speeds of a few  $km\ s^{-1}$ . In turn, interactions between the atmospheric flows and the background magnetic field give rise to Lorentz forces that can perturb the flow away from its purely hydrodynamical state. Batygin et al. (2013) showed that significant deviations from axisymmetric circulation are unstable in the presence of a non-negligible axisymmetric magnetic field, and that day- to night-side flows may only exist in objects with anomalously low magnetic fields.

**Other complexities** Many other complications in prescribing the chemical composition and thermodynamics of forming (terrestrial and giant) planets are noted elsewhere in this volume, amongst them numerous details of formation, the delivery of volatiles to terrestrial planets, atmospheric erosion, and tidal stripping.

For example, giant impacts during the phase of core formation may result in further compositional changes due to mixing and differentiation even at relatively low temperatures (Wahl & Militzer, 2015),

Giant planet migration is also likely to have a significant effect on terrestrial planet compositions (Carter-Bond et al., 2012b). The resulting large-scale mixing of material that condensed over a range of temperatures acts to increase the abundance of Mg-rich silicates in the terrestrial planet feeding zones, and thus increase the frequency of planets with Earth-like compositions compared with simulations with static giant planet orbits.

### 11.3.4 Model predictions

Structural models on their own make no predictions as to what might constitute a plausible planet, neither in terms of mass or composition, and they do not take account of formation mechanisms. Rather, specifying a mass, and some possible combination of ice, rock and iron leads, from the assumed equations of state, to its predicted radius. These models of mass as a function of composition and radius can be compared with knowledge of solar system planets to establish their plausibility, then used to provide estimates of possible exoplanet compositions on the basis of their measured mass and, in the case of transiting planets, their measured radius.

The following results on iron–rock–ice planets, and H/He dominated giants, are based on the work of Fortney et al. (2007b). More recent reviews include those by Baraffe et al. (2014), and Spiegel et al. (2014).

**Iron–rock–ice planets** Results for planets with  $M_p = 0.01 - 1000M_{\oplus}$  composed of pure iron, pure rock, and pure ice, and various ice/rock and rock/iron mixtures, are shown in Figure 11.8. It is assumed that any equilibrium structure will have differentiated gravitationally (as observed for solid bodies in the solar system), with ice overlying rock, and rock overlying iron.

In all cases, at low masses, planetary radii grow initially with mass as  $M_p^{1/3}$ . At higher mass, a larger fraction of the material becomes pressure ionised, the material behaves progressively more like a Fermi gas, and the mass–radius curves flatten near  $1000M_{\oplus}$ . Beyond this, the radius decreases as mass increases, eventually falling as  $M_p^{-1/3}$  (§6.27).

The positions of the solar system terrestrial planets, ice giants, and the Moon and Titan, are also indicated in Figure 11.8. Their known internal structures are in reasonable agreement with these theoretical models.

Determination of an unambiguous internal composition, based on measurements of  $M_p$  and  $R_p$  alone, will not be straightforward. For planets around  $1M_{\oplus}$ , for example, a mass determined with an accuracy of 50%, combined with a radius accurate to  $0.25R_{\oplus}$ , would not be sufficient to discriminate between an internal composition of pure iron, or one comprised of an equal mixture of ice and rock.

**H/He dominated gas giants** Predicted radii as a function of mass for H/He-dominated planets of age 4.5 Gyr, inferred from the models of Fortney et al. (2007b), are shown in Figure 11.9. Models include stellar heating at five orbital separations from 0.02–9.5 au, and for a range of core masses (ranging from 0–90% of the planet mass) and compositions. In general, planets with larger cores have smaller radii, and planets closer to their host stars have larger radii as a result of the additional thermal heating. The largest radii occur for core-free planets comprising pure H/He.



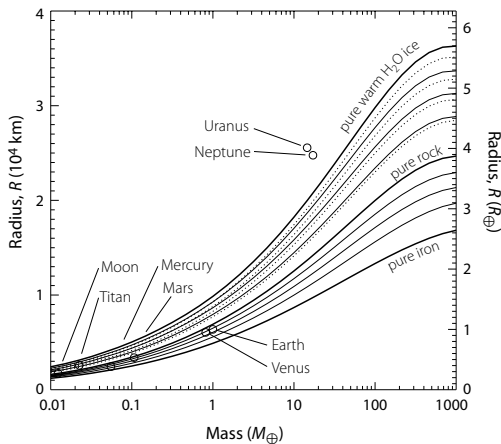


Figure 11.8: Mass versus radius for planets composed of  $\text{H}_2\text{O}$  ice, rock ( $\text{Mg}_2\text{SiO}_4$ ), and iron. The thin curves between pure ice and pure rock, are from top to bottom, 75% ice/25% rock, 50/50, and 25/75 (inner layer rock, outer ice). Dotted lines between pure warm ice and rock are for zero-temperature ice. The thin curves between rock and iron, are from top to bottom, 75% rock/25% iron, 50/50, and 25/75 (inner layer iron, outer rock). Solar system objects are shown as open circles. From Fortney et al. (2007b, Figure 4), by permission of IOP Publishing/AAS.

The solar system giants are shown in the same figure. From these models, Jupiter's position corresponds to a plausible 10% heavy element composition, with Saturn's position suggesting a higher heavy element abundance. The positions of Uranus and Neptune lie close to the 90% heavy element curves, although they probably contain more ice than rock (Podolak et al., 1995).

Knowledge about the more detailed interior composition of the solar system giants, including their rotation, core composition, ages, and possible H/He demixing, is reviewed by Guillot (2005).

**HD 149026 b** While the most massive close-in transiting planets are inferred to be gas giants, their very different densities indicate significant variations in heavy element composition. As one example, HD 149026 b has  $M_p = 0.36M_J$  and  $R_p = 0.725R_J$ , yielding  $\rho \sim 1.17 \text{ Mg m}^{-3}$ , or  $1.7\rho_{\text{Saturn}}$  (Sato et al., 2005a). For such a mass, very different radii would follow for an assumed uniform solar composition ( $1.14R_J$ ), a  $20M_{\oplus}$  core of constant-density  $\rho = 5.5 \text{ Mg m}^{-3}$  ( $0.97R_J$ ), or an object surmised to consist entirely of water ice ( $0.43R_J$ ), or of olivine ( $0.28R_J$ ). The results have rather been taken to imply the presence of a  $60 - 93M_{\oplus}$  core composed of elements heavier than H/He, corresponding to  $\sim 2/3$  heavy elements by mass, i.e. a substantial enrichment above solar composition (Sato et al., 2005a; Fortney et al., 2006b; Ikoma et al., 2006).

### 11.3.5 Terrestrial planets

**Compositional extremes** Early models of terrestrial-mass planets, and in particular those that might exist in the habitable zone, generally assumed that planets of terrestrial mass,  $\sim 0.2 - 5M_{\oplus}$ , would be of roughly terrestrial composition, i.e. made up mostly of silicates and

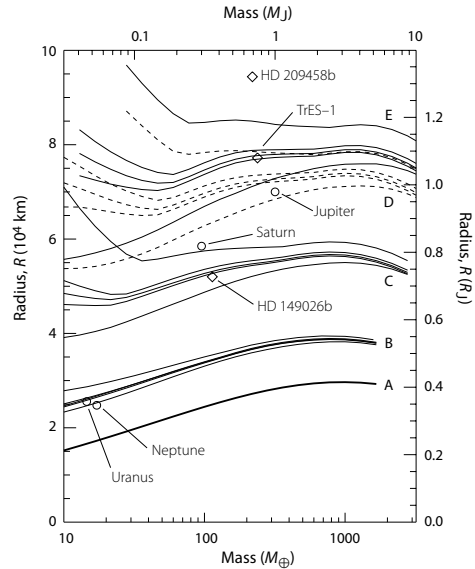


Figure 11.9: Theoretical planet radii at 4.5 Gyr as a function of mass for various compositions. For B–E, sets of five curves are calculated at 0.02, 0.045, 0.1, 1.0, and 9.5 au from the host star (top to bottom). Compositions: (A) 50% rock/50% ice; (B) 90% heavy elements; (C) 50% heavy elements; (D, dotted) 10% heavy elements; (E) pure H/He. Open circles are solar system planets, diamonds are selected exoplanets. From Fortney et al. (2007b, Figure 7), by permission of IOP Publishing/AAS.

iron-peak elements like Earth (Figure 11.2). As formation theories have advanced, it is now considered that planets of more varied and even exotic composition or structure should exist (e.g. Bond et al., 2010; Marcus et al., 2010a; Rogers & Seager, 2010a).

For example, planets formed in systems with  $C/O > 1$  might result in carbon-dominated terrestrial planets formed substantially from SiC and other carbon compounds (Kuchner & Seager, 2005; Bond et al., 2010; Madhusudan et al., 2012; Wilson & Militzer, 2014), with excess C in the mantle in some cases in the form of diamond, which would act to slow convection and diminish habitability (Unterborn et al., 2014).

Coreless terrestrial planets, without a differentiated metallic core (essentially a giant silicate mantle into which iron is bound in the form of iron oxide), could result from different oxidation states during planetary accretion and solidification (Elkins-Tanton & Seager, 2008a). Na and K clouds could surround hot super-Earths in which volatile elements have been lost (Terquem & Papaloizou, 2008; Schaefer & Fegley, 2009).

Two particular classes of Earth/super-Earth planets which are presumed to exist, and which have received specific attention, are considered in subsequent sections: the so-called 'lava planets', with a surface mostly or entirely covered by molten lava (§11.3.7), and the 'ocean planets', formed beyond the snow line with a significant mass fraction in  $\text{H}_2\text{O}$  (§11.3.8).

**General models** Various models of terrestrial exoplanets, in the mass range  $1 - 10M_{\oplus}$  and above, have been developed to predict their likely composition, and their resulting mass–radius relations (e.g. Ehrenreich et al., 2006a; Valencia et al., 2006; Seager et al., 2007; Sotin et al., 2007; Valencia et al., 2007b,c; Elkins-Tanton & Seager, 2008a,b; Grasset et al., 2009; Schaefer & Fegley, 2009; Karato, 2011; Stamenković et al., 2011; Wagner et al., 2011; Stamenković et al., 2012; Swift et al., 2012; Dorn et al., 2017b).

Models have even considered lithospheric thickness variations and different interior temperature structures (Valencia et al., 2006; Ehrenreich et al., 2006a), although effects on radii are at the few per cent level only.

**Spectra of atmosphere-free rocky planets** For terrestrial planets without an atmosphere, and considering reflection and thermal emission, Hu et al. (2012a) showed that a silicate surface is spectroscopically detectable via prominent SiO features in the thermal infrared (7–13 and 15–25  $\mu\text{m}$ ), with structures wide enough to be distinguished from atmospheric features, and perhaps sufficient to distinguish between primary crust (from a magma ocean or high-temperature lavas), and water ice or hydrated silicates (implying extant or past surface water). More detailed surface and atmospheric diagnostics have also been considered (Kaltenegger et al., 2012).

**Equation of state** Information required to determine the mass–radius relation (ignoring heat transport) is contained in the equations for hydrostatic equilibrium and mass conservation (Equations 11.9 and 11.11), and in the equation of state giving the thermodynamic relation between pressure and density  $P(\rho, T)$ . Some published models have been computed without temperature dependence (e.g. Seager et al., 2007), and others with (e.g. Valencia et al., 2006, 2007c; Sotin et al., 2007).

The adopted equation of state may rest partly on empirical fits to experimental data obtained at pressures  $P \lesssim 200$  GPa, such as the formulations of Vinet or Burch–Murnaghan or, at high pressures  $P \gtrsim 10^4$  GPa as the electron degeneracy pressure becomes increasingly important, on the Thomas–Fermi–Dirac theoretical formulation. Further details are given by, e.g., Seager et al. (2007) and Sotin et al. (2007, their Appendix A).

By way of illustration, the simplest form adopted by Seager et al. (2007) is that of Vinet et al. (1989)

$$P = 3K_0\eta^{2/3} \left[ 1 - \eta^{-\frac{1}{3}} \right] \exp\left( \frac{3}{2}(K'_0 - 1) \left[ 1 - \eta^{-\frac{1}{3}} \right] \right), \quad (11.14)$$

where  $\eta = \rho/\rho_0$  is the compression ratio,  $K_0 = -V(\partial P/\partial V)_T$  is the bulk modulus of the material, and  $K'_0$  is the pressure derivative. Similar dependencies are shown in Figure 11.3. Seager et al. (2007) have noted that the constant temperature equations of state for the solid materials they considered can be approximated by

$$\rho(P) = \rho_0 + cP^n. \quad (11.15)$$

They list best-fit parameters  $\rho_0$ ,  $c$ , and  $n$  for various materials over the range  $P < 10^{16}$  Pa, with these approximations valid to some 1–10% depending on pressure.

**Example results and ternary diagrams** Valencia et al. (2007b) modeled a general low-mass exoplanet comprising concentric differentiated shells of homogeneous composition, and solved the differential equations for density, pressure, mass, and gravity structure under hydrostatic equilibrium within each layer.

The regions adopted are: (1) the core, mainly Fe, divided into inner solid and outer liquid layers if the temperature profile crosses the Fe melting curve; (2) an upper and lower mantle comprising various Mg-Fe silicates and oxides; and (3) a H<sub>2</sub>O layer divided into a water ocean over an icy shell comprising the high-pressure ices VII and X. The thicknesses of the regions depend on the ice-mass and core-mass fractions.

A selection of their results are shown in the form of *ternary diagrams* in Figure 11.10. In these, the data of a three-component system are plotted in a triangle whose sides depict the three compositional axes. Each vertex represents 100% of the given component, with the opposite side corresponding to 0% of that component, and lines parallel to that side indicating the percentage of that component. The radius of a planet is then determined by the model for any combination of components and for a given mass. Different ternary diagrams show the radius (or other properties) for a specific planet mass.

Certain regions of the overall composition space are likely to be excluded on the basis of plausible nebula abundances and accretion mechanisms, and these are shown shaded in Figure 11.10a. The minimum planet radius, for pure Fe or a heavy Fe+Ni alloy, occurs at the lower right vertex, and correspondingly for the maximum radius assuming a pure H<sub>2</sub>O composition at the lower left. Allowing for excluded regions, the minimum and maximum radii are unlikely to fall at the vertices.

The isoradius diagrams of Figures 11.10b–c show that the same value of the radius is obtained for different combinations of core, mantle, and water content, illustrating the degeneracy in composition which results from a knowledge only of the density. But some constraints on composition follow from the fact that there will be a threshold radius such that larger values imply that the planet is ocean-dominated. This is given by the largest isoradius curve that intersects the ‘terrestrial side’ (zero water content) of the ternary diagram. For 1, 2.5, 5, 7.5, and  $10M_{\oplus}$  planets, the threshold radius is 6600, 8600, 10400, and 11600 km respectively. These arguments have been applied to the  $7.5M_{\oplus}$  GJ 876 d by Valencia et al. (2007c).

### 11.3.6 Analytical model for rocky interiors

An analytical model for rocky planet interiors, based on the assumption that the internal gravity increases linearly in the core, and stays constant in the mantle, is given by Zeng & Jacobsen (2017). From this, they infer a number of scaling relations, replicating values for the Earth, and applied to observational data for GJ 1132 b, Kepler–20 b, and Kepler–93 b. These include:

(i) the core mass fraction is related to the core radius fraction by (Zeng & Jacobsen, 2017, equ 13)

$$\text{CRF} \approx \sqrt{\text{CMF}}; \quad (11.16)$$

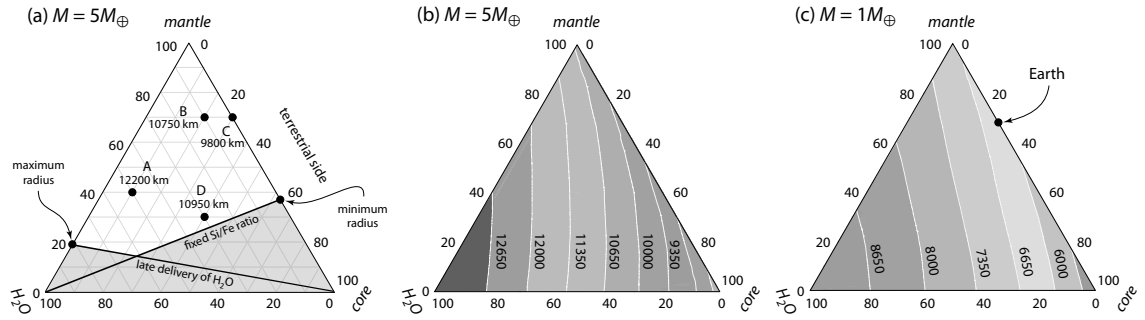


Figure 11.10: Ternary diagrams with radius predictions for super-Earth models based on arbitrary compositions of a Fe-core/silicate mantle/ $\text{H}_2\text{O}$ -layer planet. In (a), for  $M = 5M_\oplus$ , four different compositions are labeled (CMF = core mass fraction, IMF = ice mass fraction): (A) CMF=10%, IMF=50%,  $R = 12200$  km; (B) CMF=20%, IMF=10%,  $R = 10750$  km; (C) CMF=30%, IMF=0%,  $R = 9800$  km; and (D) CMF=40%, IMF=30%,  $R = 10950$  km. The shaded regions show improbable compositions from solar nebula abundances and accretion processes. In (b,c), contours of equal radius are shown as a function of the three-component composition for total planet masses of  $M = 5M_\oplus$  and  $M = 1M_\oplus$  respectively. Earth has a negligible mass in water, and so appears on the side opposite the  $\text{H}_2\text{O}$  vertex. From Valencia et al. (2007b, Figures 1–2), by permission of IOP Publishing/AAS.

(ii) the typical interior pressure, evaluated at the core–mantle boundary, is (Zeng & Jacobsen, 2017, equ 15)

$$P_{\text{CMB}} = P_{\text{typical}} \ln\left(\frac{1}{\text{CMF}}\right) = \frac{g_s^2}{4\pi G} \ln\left(\frac{1}{\text{CMF}}\right); \quad (11.17)$$

(iii) an estimate of the energy released in core formation is given by the difference between the total gravitational energy, and the gravitational energy of a uniform sphere, as (Zeng & Jacobsen, 2017, equ 29)

$$E_{\text{diff}} \approx \frac{1}{15} \frac{GM_p^2}{R_p} \approx \frac{1}{10} |E_{\text{grav}}|, \quad (11.18)$$

implying that the energy released during core formation is  $\sim 10\%$  of the total gravitational energy of such a rocky planet. For Earth,  $E_{\text{diff},\oplus} \approx 2.5 \times 10^{31}$  J;

(iv) the effective heat capacity of the mantle,  $C_{\text{th,mantle}}$ , can be defined with respect to the *mantle potential temperature*,  $T_{\text{mp}}$  (Zeng & Jacobsen, 2017, equ 35)

$$C_{\text{th,mantle}} \approx \frac{3R}{\mu} M_p \approx 7 \times 10^{27} \left(\frac{M_p}{M_\oplus}\right) \text{JK}^{-1}, \quad (11.19)$$

while a detailed calculation gives the heat capacity of the Earth’s mantle as  $7.4 \times 10^{27}$   $\text{JK}^{-1}$  (Stacey & Davis, 2008);

(v) the moment of inertia can be approximated by (Zeng & Jacobsen, 2017, equ 40)

$$I_{\text{planet}} \approx \frac{1}{3} M_p R_p^2. \quad (11.20)$$

For Earth,  $M_\oplus R_\oplus^2 = 2.4 \times 10^{38}$   $\text{kg m}^2$ , and  $I_\oplus \approx \frac{1}{3} M_\oplus R_\oplus^2 = 8 \times 10^{37}$   $\text{kg m}^2$ . Earth’s rotational angular momentum is  $L_\oplus = I_\oplus \times \Omega_\oplus = 6 \times 10^{33}$   $\text{kg m}^2 \text{s}^{-1}$ . The total rotational energy is  $E_{\text{rot}} = \frac{1}{2} I_\oplus \Omega_\oplus^2 = L_\oplus^2 / (2\Omega_\oplus^2) = 2 \times 10^{29}$  J, where  $\Omega_\oplus = 7.3 \times 10^{-5}$   $\text{rad s}^{-1}$  is the angular rotation frequency.

### 11.3.7 Lava planets

A *lava planet*, or ‘lava ocean’ or ‘magma ocean’ planet, is a hypothetical subset of terrestrial (Earth/super-Earth) planet, with a surface mostly or entirely covered by molten lava. This might exist on close-in tidally-locked rocky planets, subject to intense irradiation and/or tidal heating, or on young terrestrial planets shortly after formation, as a result of internal or impact heating.

**Close orbiting** Close-orbiting lava planets are considered to be characterised by  $R_p \lesssim 2R_\oplus$  and  $M_p \lesssim 10M_\oplus$ , a measured mass and radius indicating rocky composition, and very short orbital period,  $P \lesssim 1$  d,  $a \lesssim 0.02$  au (Léger et al., 2009, 2011b; Rouan et al., 2011).

The star–planet proximity results in rapid spin–orbit synchronisation (§10.11.5), a day-side continuously facing the star, and high temperatures (2500–3000 K) at the substellar point. Fusion and vapour fractionation of rocks produces a ‘lava ocean’ of refractory components extending over much of the day-side. The night-side is in perpetual darkness, and much colder ( $\sim 50$ –75 K).

Suggested examples include CoRoT–7 b (Léger et al., 2009), Kepler–10 b (Batalha et al., 2011; Rouan et al., 2011), and Kepler–78 b (Sanchis-Ojeda et al., 2013a).

**Impact heated** Especially during the post-oligarchic phase of terrestrial planet formation (§10.4.5), head-on collisions can lead to mergers with little mass loss. Large impacts cause extensive heating and the formation of lava or magma oceans (Tonks & Melosh, 1992).

With the delivery of a substantial amount of water during planet formation (Morbidelli et al., 2000; Raymond et al., 2007a; Walsh et al., 2011), and on the basis that giant impacts do not entirely erode  $\text{H}_2\text{O}$  inventory (Genda & Abe, 2005), such early molten planets are likely to be covered by a steam-rich atmosphere.

**Emergent spectra** Emergent spectra of hot molten planets have been investigated for different atmospheric compositions, including H<sub>2</sub>O-rich atmospheres. Miller-Ricci et al. (2009) derived the expected thermal emission spectra, considering various possible atmospheric compositions: solar and enhanced metallicity, H<sub>2</sub>O–CO<sub>2</sub> dominated, and Venusian.

At early stages of evolution, the highest fraction of water is expected to dissolve in a deep magma ocean because of its high solubility into silicate melts (Zahnle et al., 1988). The steam atmosphere therefore accounts for a modest fraction of its total inventory. As solidification proceeds, the silicate magma becomes enriched in H<sub>2</sub>O, and degases at a rate that depends on the solidification rate of the magma ocean (e.g. Elkins-Tanton, 2008). Whether the steam atmosphere grows with time depends on the net balance of the degassing of water from the interior and its loss rate by hydrodynamic escape.

Hamano et al. (2013) showed that for a magma ocean covered with a steam atmosphere, terrestrial planets have a distinct early evolution that depends on whether the orbital distance from the host star is within or beyond the critical distance at which the stellar heating flux is equal to the radiation limit of the planet's steam atmosphere. Beyond this critical distance the thermal emission declines on a time scale  $\leq 10^6$  yr, while within it, the planet will emit significant near-infrared thermal radiation for the full lifetime of the magma ocean (Marcq, 2012; Lebrun et al., 2013; Hamano et al., 2015; Marcq et al., 2017).

Other studies cover prospects for detection of molten terrestrial planets (Hamano et al., 2015), models of the expected emission spectra (Ito et al., 2015), implications for Earth's cooling, and a geodynamo sustained only by core cooling over 4 Gyr (Monteux et al., 2016a), simulations of the onset of solid-state mantle convection and mixing during magma ocean solidification (Maurice et al., 2017), models of the volatile loss during the magma ocean phase (Dhaliwal et al., 2018), and the relative influence of H<sub>2</sub>O and CO<sub>2</sub> on the primitive surface conditions of rocky planets (Salvador et al., 2017).

### 11.3.8 Ocean planets

**Hypothetical existence** Kuchner (2003) and Léger et al. (2004) hypothesised that large terrestrial- or super-Earth mass planets could exist with compositions dominated by volatiles such as H<sub>2</sub>O ice. Termed *ocean planets* or 'water worlds', these could form at large orbital distances, beyond the snow line (§11.2.3). Although an increased fraction of more volatile ices (NH<sub>3</sub>, CH<sub>4</sub>, CO, N<sub>2</sub>, CO<sub>2</sub>) would be expected for objects forming further out (Gilliam & McKay, 2011), longer times would be required to reach chemical equilibrium at these lower temperatures and densities (§11.2.2).

Such objects in the range  $1 - 10M_{\oplus}$ , and thus below the presumed core masses required for giant planet formation, would not have accreted a large H/He envelope. A fraction could thereafter have migrated inwards, some plausibly to reside in the habitable zone.

With suppressed topography and deep oceans, most should be entirely water covered. Lacking a silicate weathering thermostat, their climate is then predicted to be less stable than those with exposed continents, with a continuously habitable zone much narrower than for Earth-like planets.

**Atmospheres** Kuchner (2003) argued that a H<sub>2</sub>O-dominated planet arriving at 1 au should quickly develop a gaseous atmosphere of  $\geq 10^7$  Pa, under conditions similar to those hypothesised during Earth's accretion history (Abe & Matsui, 1985). In this scenario, shock impact degassing of volatile materials results in the formation of an impact-generated proto-atmosphere, and the planet's surface temperature thereafter increases with subsequent planetesimal impact due to the atmosphere's blanketing effect.

If accretion-driven impact energy at its base exceeds a certain value, the atmosphere can become a runaway greenhouse. Otherwise, the hot atmosphere provides stable greenhouse heating up to a basal temperature (Matsui & Abe, 1986; Kuchner, 2003)

$$T_G = \left( \frac{\lambda + \sqrt{1 - \omega}}{1 + \sqrt{1 - \omega}} \right)^{1/4} T_{\text{BB}} \approx \lambda^{1/4} T_{\text{BB}}, \quad (11.21)$$

where  $\lambda$  is the ratio of infrared to optical opacities,  $\omega$  is the *single scattering albedo* at short wavelengths, and  $T_{\text{BB}}$  is the local blackbody temperature

$$T_{\text{BB}} = 278 \text{ K} \left( \frac{a}{1 \text{ au}} \right)^{-1/2} \left( \frac{L_{\star}}{L_{\odot}} \right)^{1/4}. \quad (11.22)$$

For  $\lambda \sim 10 - 100$  ( $\sim 31$  for Venus), and  $\omega \sim 1$ ,  $T_G \sim 2.4 T_{\text{BB}}$ .

When  $T_G < T_{\text{crit}} = 647 \text{ K}$ , the *critical temperature*, water condenses out of a vapour atmosphere in equilibrium with the stellar radiation, leaving a hot ocean on the planet's surface (Matsui & Abe, 1986; Zahnle et al., 1988). Again assuming  $\lambda = 31$ ,  $\omega = 1$ , the planet's vapourisation halts for  $a \geq 1.03 \text{ au}$   $(L_{\star}/L_{\odot})^{1/2}$ , and the planet can survive indefinitely, so long as it retains its atmosphere<sup>2</sup>. Closer in, the planet will slowly vaporise.

The effect of continued giant impacts on the bulk composition of H<sub>2</sub>O-rich super-Earths was considered by Marcus et al. (2010b), and the persistence of such oceans on super-Earths in the presence of a deep-water cycle, plate tectonics, and mantle convection, by Schaefer & Sasselov (2015). They found that super-Earths may be less habitable in their early years than smaller planets, but their habitability will persist for much longer.

Deep global oceans result, however, in the formation of high-pressure H<sub>2</sub>O-ice, separating the planetary crust from the liquid ocean, and hence from the atmosphere (Kitzmann et al., 2015; Komacek & Abbot, 2016; Levi et al., 2017b). Instead of a carbonate–silicate cycle as on Earth (§12.3.5), the atmospheric CO<sub>2</sub> concentration is governed by the ocean's capability to dissolve it.

<sup>2</sup>Matsui & Abe (1986) used such arguments to infer the temperature of the first rain on Earth of  $\sim 600 \text{ K}$ . They considered this to be consistent with the wide temperature limits of the early Archean ( $\sim 3.5 \text{ Ga}$ ) ocean of  $\sim 273 - 419 \text{ K}$  as estimated from the <sup>18</sup>O isotope composition of metamorphosed sedimentary rock by Oskvarek & Perry (1976).

Kitzmann et al. (2015) found that, in contrast to the stabilising carbonate–silicate cycle regulating the long-term CO<sub>2</sub> inventory of Earth’s atmosphere, the CO<sub>2</sub> cycle feedback on ocean planets is negative, and has strong destabilising effect on its climate. Levi et al. (2017b) found that, in a steady state, the atmospheric CO<sub>2</sub> abundance has two possible states, one in which wind-driven circulation is the dominant CO<sub>2</sub> exchange mechanism and an atmosphere of tens of bars of CO<sub>2</sub> results, and another when sea-ice formation dominates as the CO<sub>2</sub> deposition mechanism, when an atmosphere of a few bars of CO<sub>2</sub> is established. This suggests the possibility of a negative feedback mechanism, unique to water planets, where a reduction in the subpolar temperature drives more CO<sub>2</sub> into the atmosphere to increase the greenhouse effect.

**Candidate ocean planets** GJ 1214 b, at 13 pc, was discovered as a transiting planet by Charbonneau et al. (2009). With  $M = 6.55M_{\oplus}$  and  $R = 2.68M_{\oplus}$ , its low density ( $\rho = 1.9 \text{ Mg m}^{-3}$ ), could be modeled by a dense iron–silicate core, combined with a H–He envelope. But its small mass argues against the accretion of an extended gaseous envelope, and suggest instead an internal composition comprising a Fe–Ni core, a silicate mantle, some 50% of its mass in H<sub>2</sub>O, and possibly a thin outer H–He envelope (Marcy, 2009a). A deep liquid H<sub>2</sub>O ocean, and a hot vapour atmosphere, are suggested by its equilibrium surface temperature of  $\sim 460 \text{ K}$  ( $\sim 190 \text{ C}$ ).

A cold ocean planet model was introduced for the low-temperature microlensed planet OGLE–2005–BLG–390L b (Ehrenreich et al., 2006a).

Given the compositional range that can match a given bulk density (at least for smaller radii planets), the secure identification of ocean planets based on the mass–radius relation alone may still be questionable unless a significant gas layer can be excluded by other means (Adams et al., 2008).

**Ocean depth** Amongst other investigations, Léger et al. (2004) considered a representative  $6M_{\oplus}$  ocean planet, comprising  $3M_{\oplus}$  of metals and silicates and  $3M_{\oplus}$  of H<sub>2</sub>O. Depending on orbital radius and thermal properties, the outer H<sub>2</sub>O envelope could exist as a hot gaseous phase for which, at  $P_{\text{crit}}$ ,  $T > T_{\text{crit}}$ , such that no liquid surface exists. At progressively lower temperatures, it would have either a liquid or ice surface.

For a planet in the habitable zone with a liquid water surface, Léger et al. (2004) posed the question: ‘*how deep is the ocean?*’. Because of the nature of the ice phase space, this apparently loosely-constrained question has a rather well-defined answer. For a given surface temperature, and depending on the internal planetary heat being transferred outwards, the increasing temperature as a function of depth has its maximum gradient for an adiabatic dependency, a zero gradient for a perfectly isothermal convection-driven transfer, and even a negative gradient as a result of large-scale currents as in the Earth’s ocean.

The pressure–temperature relations for the adiabatic and isothermal dependencies are shown in the inset of Figure 11.5 for an ocean surface at  $T = 7^{\circ}\text{C}$ . The bottom of the ocean is encountered at the pressure at which the water solidifies, i.e. the intercept of the isotherm or adiabat with the liquid–solid (actually ice VI) phase boundary. For an adiabatic dependency, and an ocean surface at 0, 7, 30°C (273, 280, 303 K) the resulting

ocean depth is 60, 72, and 133 km respectively. For an isothermal ocean at the same surface temperatures, the ocean depth is 40, 45, and 65 km respectively. Similar considerations, and similar results, were given by Sotin et al. (2007).

**Ice-covered water worlds** Fu et al. (2010) modeled the thermal and dynamical structure of the near-surface for icy and oceanic surfaces, finding separate regimes (according to surface temperature, heat flux, and gravity) where the planet is expected to maintain a subsurface liquid ocean and where it is expected to exhibit ice tectonics.

Even for a fully ice-covered planet, geothermal heat from the planet interior may melt the interior ice, creating an internal ocean covered by an ice shell. Models by Ueta & Sasaki (2013) show that a  $1M_{\oplus}$  planet at 1 au, and with 0.6–25 times the H<sub>2</sub>O mass of Earth could have an internal ocean. High-pressure ice layers may appear between the internal ocean and the rocky core on a planet with an H<sub>2</sub>O mass over 25 times that of Earth.

**Water cycling between ocean and mantle** Cowan & Abbot (2014) considered the partitioning of water between ocean and mantle. They demonstrated that, since hydrostatic sea-floor pressure is proportional to surface gravity, super-Earths with a deep-water cycle will tend to store more water in their mantle. They conclude that a tectonically-active terrestrial planet of any mass can maintain exposed continents if its water mass fraction is less than  $\sim 0.2\%$ , significantly increasing the possibility that super-Earths are habitable. Their greatest source of uncertainty is Earth’s current mantle water inventory (§12.3.4): the greater its value, the more robust planets are to inundation.

**Solar system icy bodies** Three classes of solar system object have a higher fraction of ices than either the terrestrial planets or the gas giants: comets, the ice giants Uranus and Neptune, and the icy satellites of the outer planets (Johnson, 2005).

The interior structures and cooling histories of Uranus (Podolak et al., 1991) or Neptune (Hubbard et al., 1995) are still held to be less well understood than those of Jupiter or Saturn. But they are of too low a density to be comprised solely or predominantly of ices (Figure 11.8), and models for their interiors suggest H/He envelopes around massive protoplanetary cores of rock and ice (Figure 11.2). Ices in their interiors are expected to be in a fluid phase (Cavazzoni et al., 1999). The existence of H<sub>2</sub>O oceans deep in their interiors has been considered by Wiktorowicz & Ingersoll (2007).

Icy satellites such as JIII Ganymede, JIV Callisto, SV Rhea and SVIII Iapetus are of much lower masses, typically  $\leq 0.02 - 0.001M_{\oplus}$ , but have significantly higher ice fractions. Their inferred compositions, mostly ices and silicates, are consistent with formation near the snow line. They are believed to have formed very rapidly, on time scales of 100–10 000 years in the case of Ganymede and Callisto (Lunine & Stevenson, 1982). During their assembly, optically thick gaseous envelopes would have prevented them from dissipating the heat of accretion by radiation, and they are presumed to have begun life with their ice mostly melted, before freezing again in the outer solar system (Lunine & Stevenson, 1982).

## 11.4 Planet atmospheres

Atmospheric modeling aims to derive the properties of a planet’s outer gaseous envelope, notably the pressure–temperature profiles of their outer regions, day–night temperature gradients and circulation patterns, their

chemical and condensate composition, and their spectral properties including broad-band colours as well as more detailed predictions of the presence of molecular bands and atomic lines in the optical and infrared (e.g. Seager, 2010; Seager & Deming, 2010; Heng, 2017).

Many factors influence the pressure–temperature structure of the outer atmosphere. These include the age of the planet combined with its cooling rate, its internal (radiogenic and tidal) heat sources, external heating due to stellar irradiation, and the physical and chemical properties of the atmospheric constituents, notably abundances, gas opacities (box, page 570), and the specific condensed phases present at the relevant temperatures and pressures. For gas giants, coupling of atmosphere models to interior thermal evolution models is required to provide a more self-consistent insight into their combined interior and atmospheric structures.

**Outline of the treatment** Given these various complexities, the treatment here is structured as follows. Section 11.4.1 divides the understanding and modeling of giant planet atmospheres into a number of discrete topics. While these are, to a greater or lesser extent, relevant to all planetary atmospheres, they are presented in the context of the primordial H/He-rich atmospheres accreted during giant planet formation. Some of the key features of giant planet atmospheres are, in turn, strongly influenced by their host star proximity; although the resulting intense non-uniform stellar irradiation makes these ‘hot Jupiters’ atypical of the overall giant planet population, they dominate the planets that can be studied in any sort of detail, via transmission and emission spectroscopy, at the present time.

All planet atmospheres are subject to some form of atmospheric circulation (winds). The extreme stellar irradiation of hot Jupiters has a particularly strong influence on their atmospheric circulation, and on associated aspects such as their chemical equilibrium and pressure–temperature profiles. These aspects are noted in Section 11.4.1, but a self-contained treatment of atmospheric circulation is deferred to Section 11.4.2.

Section 11.4.3 turns to the atmospheres of terrestrial planets, their likely formation mechanisms, and the associated studies of atmospheric circulation. Section 11.4.4 provides a short diversion into the predicted atmospheres of ejected planets. Section 11.4.5 deals with processes that can erode planetary atmospheres.

Section 11.5 then considers the form of the mass–radius relation that follows from models of planet interiors and atmospheres.

These detailed models are central to the interpretation of transit and eclipse spectroscopic observations, which are considered in Section 11.6. They are also central to considerations of planet habitability, considered in Section 11.7.

### 11.4.1 Atmospheres of gas giants

Numerous considerations and effects are involved in characterising and modeling an (irradiated and circulating) giant planet atmosphere. They are described here as a series of somewhat self-contained topics which are, of course, interconnected in practice.

**Elemental composition and enrichment** Measured bulk densities for transiting giant planets, as well as formation models, indicate massive H/He-rich envelopes surrounding a denser core of metals, silicates, and ices in various proportions. Atmospheric models frequently use elemental abundance ratios inferred for the solar nebula (§12.1.3), thereafter computing equilibrium compositions at various metallicities (e.g. Fegley & Lodders, 1994; Lodders & Fegley, 2002; Fortney et al., 2008b).

The solar system gas giant atmospheres are known to be enriched in at least some heavy elements with respect to the Sun, by a factor of ~2–5. Estimates for a number of elements for Jupiter’s atmosphere (O, C, N, S, and various noble gases) were originally made from measurements with the Galileo entry probe (Niemann et al., 1998; Atreya et al., 2003), with measurements of C and P for Saturn from Cassini and ISO spectroscopy (Flasar et al., 2005; Visscher & Fegley, 2005).

Processes which caused such enrichment are uncertain, and whether they operate to a similar degree in exoplanet atmospheres is unknown. Nevertheless, various enrichment mechanisms have been suggested for Jupiter and Saturn, including planetesimal bombardment and accumulation during their formation (Owen et al., 1999; Gautier et al., 2001b,a; Alibert et al., 2005d), erosion of the heavy-element core (Stevenson, 1985), accretion of a metal-rich disk gas (Guillot & Hueso, 2006), and chemical fractionation within the planet (Stevenson & Salpeter, 1977a; Lodders, 2004b).

Models based on the assumption of *chemical equilibrium* perform a global minimisation of the system’s *Gibbs free energy*, viz. the thermodynamic potential that is minimised when a system reaches chemical equilibrium at constant pressure and temperature (e.g. Burrows & Sharp, 1999; Lodders & Fegley, 2002). The approach calls for the inclusion of thermochemical data for hundreds of compounds, and allows the concentrations of all species to be solved for simultaneously. Once the elemental abundances in the atmosphere have been specified, chemical abundances depend, to a first approximation, only on the local temperature and pressure.

**Atmospheric models** For an ideal gas in hydrostatic equilibrium, the number density of molecules per unit area above a specified altitude  $z$  is given by

$$N \sim \frac{p(z)}{\mu g(z)} = n(z) H, \quad (11.23)$$

where  $\mu$  is the mean molecular weight,  $H$  is the atmospheric scale height,  $p(z)$  is the pressure, and  $g(z)$  is

the gravity. The equality, exact for an isothermal gas, provides an insight into a number of the basic characteristics of atmospheres (Chamberlain & Hunten, 1987; Houghton, 2002), including that of the Earth.

The complexity of radiation transfer through an atmosphere whose absorption properties depend on atomic and molecular composition, and on temperature and pressure, means that numerical models, based on 1d radiative transfer codes, are required to predict their detailed (pressure–temperature) structures (e.g. Toon et al., 1989). Condensation processes, or *rainout*, are also taken into account. Since these are, in turn, dependent on temperature and pressure, the construction of atmospheric models is essentially an iterative process.

The model described by Fortney et al. (2008b) computes radiative–convective equilibrium pressure–temperature profiles and low-resolution spectra, with high-resolution spectra computed using a line-by-line radiative transfer code. Models may be based on solar nebula abundances (e.g. Lodders, 2003) or others, and tables of relevant opacities (e.g. Freedman et al., 2014, see also box, page 570).

**Detailed models** Another comprehensive atmospheric modeling programme widely applied to brown dwarf and (irradiated) giant exoplanet atmospheres is described by Burrows et al. (2008a). Model atmospheres are computed using the code CoolTLUSTY (Sudarsky et al., 2003; Hubeny et al., 2003; Burrows et al., 2006b), a variant of the general atmosphere code TLUSTY (Hubeny, 1988; Hubeny & Lanz, 1995). Molecular and atomic opacities were taken from Sharp & Burrows (2007). Chemical abundances, including condensate rainout, are derived using thermochemical modeling (Burrows & Sharp, 1999; Burrows et al., 2001; Sharp & Burrows, 2007).

Such models have been applied to the atmospheres of a variety of planetary and substellar objects, including • Titan (McKay et al., 1989); • Uranus (Marley & McKay, 1999); • brown dwarfs and (irradiated) transiting hot Jupiters in general (Burrows et al., 1997; Marley et al., 1999; Burrows et al., 2000a; Chabrier & Baraffe, 2000; Sudarsky et al., 2000; Burrows et al., 2001; Hubeny et al., 2003; Sudarsky et al., 2003; Burrows et al., 2004b; Sudarsky et al., 2005; Burrows et al., 2006b, 2007a,b; Tinetti et al., 2007a; Burrows et al., 2010); • ultracool brown dwarfs (Marley et al., 2002; Saumon & Marley, 2008); • specific T dwarfs including GJ 229 B and others (Marley et al., 1996; Saumon et al., 2006, 2007); and • many individual transiting giant exoplanets, starting with TrES-1 and HD 209458 b (Burrows et al., 2005; Fortney et al., 2005; Baraffe et al., 2003), HD 149026 b (Fortney et al., 2006b), and HD 209458 b and HD 189733 b observed by Spitzer (Fortney & Marley, 2007).

**Pressure–temperature relations** Examples of derived pressure–temperature relations are given in Figures 11.11–11.12, both partly anticipating descriptions of the effects of external heating. Figure 11.11 shows model predictions for Jupiter, for a selection of T, L and M dwarfs, and for giant stars with  $T_{\text{eff}} = 3000$  K and a range of surface gravities. The 800 K T dwarf corresponds to GJ 570 D, while the 1000–960 K T dwarf corresponds to GJ 229 B.

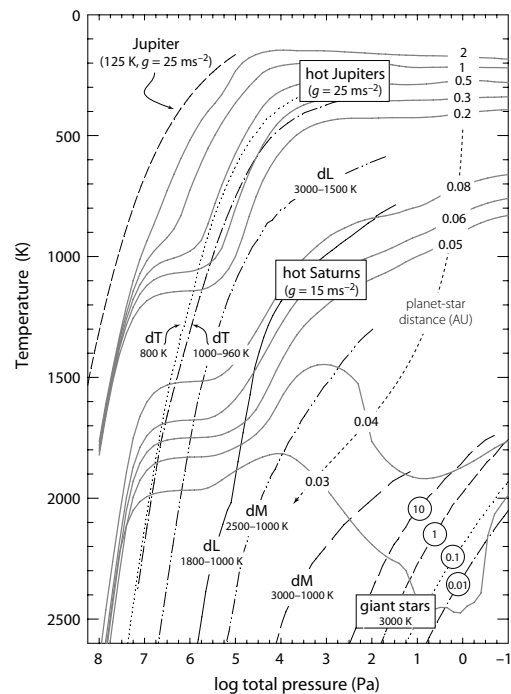


Figure 11.11: Pressure–temperature relations from model atmospheres. Thin lines, labeled with  $T_{\text{eff}}$ , show relations for (upper left to lower right) Jupiter; T, L, M dwarfs; and giant stars, for which circled numbers indicate surface gravity,  $g$ , in  $\text{m s}^{-2}$ . Thick lines are relations for Jupiter- and Saturn- mass planets at different distances from their primary stars, labeled in au. Temperature and pressure increase to the lower left, as if towards the interiors. From Lodders (2010, Figure 4).

The effective temperatures of gas giant planets of a given mass which are not externally heated decrease with age, as for brown dwarfs after the completion of deuterium burning (Burrows et al., 2001, 2003b, see also Figure 9.3). Correspondingly, in the absence of any external heating, the chemistry of their outer atmospheres will also change with age.

Figure 11.12 shows results for two of the six close-in planets modeled by Burrows et al. (2008a). These models include an *ad hoc* upper atmosphere absorber with constant opacity,  $\kappa_e$ , consistent with the expected abundances for TiO and VO. The effects of energy transport from day-side to night-side, deep in the atmosphere, is characterised by the parameter  $P_n$ , ranging from 0 (no energy redistribution) to 0.5 (full redistribution).

**External heating** By modifying the pressure–temperature relation in its outer regions, an external heat source in the form of stellar irradiation affects the mass–radius of a giant planet, as considered in §11.3.3. The same effects modify the emission spectrum of the planet, by altering the pressure–temperature structure, and thereby also modifying the conditions for condensation of atomic and molecular species.

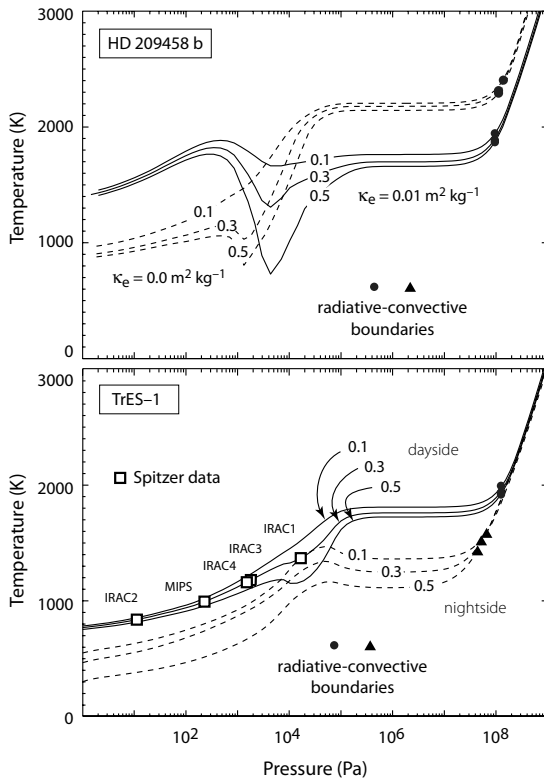


Figure 11.12: Pressure–temperature profiles for two of the six close-in planets modeled by Burrows et al. (2008a). Day-side profiles incorporate stellar irradiation. Numbers for each curve are the values of  $P_n$  which characterise the efficiency of irradiated energy transfer from day-side to night-side, ranging from 0 (no energy redistribution) to 0.5 (full redistribution). Models for HD 209458 b include an extra upper-atmosphere absorber, characterised by  $\kappa_e$ . When  $\kappa_e \neq 0$ , the pressure–temperature profiles show distinct thermal inversions. From Burrows et al. (2008a, Figures 1a,c), by permission of IOP Publishing/AAS.

Figure 11.11 also shows the consequences of external heating on the pressure–temperature relations for Jupiter- and Saturn-mass exoplanets over a range of separations (0.03–2 au) from their host star. Planets of Jupiter mass, with  $T_{\text{eff}} \sim 100$  K in the absence of stellar heating (upper lines), display modified pressure–temperature profiles at smaller orbital separations which resemble those of isolated T dwarfs (Fortney et al., 2008b). However, their different surface gravities result in different opacities at a given atmospheric pressure and temperature, resulting in different  $T_{\text{eff}}$  for giant planets and brown dwarfs at a given location in the pressure–temperature diagram.

At smaller orbital separations, the atmospheres of planets such as TrES-1 b and HD 209458 b reach temperatures of 1200–1400 K or higher, resulting in atmospheric chemistry more comparable to that of isolated brown dwarfs near the L–T dwarf transition.

At the closest separations of 0.04–0.03 au are the very short-period transiting planets such as TrES-3 b. Occupying the lower-right region of Figure 11.11, temperatures in the outer regions are high and pressures are low, corresponding to conditions in giant and supergiant stellar atmospheres. Stratospheric-type temperature inversions are predicted by these models.

**Temperature inversions and stratospheres** The upper atmospheres of hot Jupiters are radiation dominated, with the radiation efficiency depending on the emission and absorption of the molecules present. Generally, stellar irradiation is expected to penetrate the atmosphere to a significant depth, heating it from below, and resulting in temperatures that decrease with increasing altitude. However, strong optical or ultraviolet absorbers in the upper layers can heat up, blocking energy escape from lower levels, and leading to a *thermal inversion*, i.e. a layer in which the temperature *increases* with altitude (e.g. Hubeny et al., 2003; Guillot, 2010).

The full temperature profile in radiative-equilibrium can be constructed by extending the classical Milne atmosphere with an irradiation term, including a ‘dilution factor’ accounting for stellar irradiation being strongest at the substellar point rather than isotropic (e.g. Hubeny et al., 2003; Hansen, 2008; Guillot, 2010; Heng et al., 2011a; Burrows, 2014b; Drummond et al., 2016).

Theoretical day-side pressure–temperature profiles for various transiting hot Jupiters are shown in Figure 11.13. Temperatures can vary, depending on  $T_{\star}$  and dilution factor, by  $\sim 1000$ – $2000$  K, while differences in upper atmospheres between ‘inverted’ and ‘non-inverted’ cases reach  $\sim 1000$ – $1500$  K, which translates into flux spectrum differences of factors  $\sim 2$ – $4$  (Figure 11.13, bottom panel). Additional upper atmosphere absorbers can also lead to mid-infrared spectra that vary significantly for the same stellar irradiation.

Such temperature inversions have been identified through photometry and transmission spectroscopy, e.g. from elevated Spitzer–IRAC fluxes in certain bands (in particular at  $5.8 \mu\text{m}$ ), for a number of strongly irradiated gas giants, e.g. for HD 209458 b and TrES-4 b (§11.6). TiO and VO are considered to contribute to the high-altitude opacity necessary to generate this temperature inversion (Hubeny et al., 2003; Fortney et al., 2008a; Spiegel et al., 2009b), although contributions from other photochemical haze are indicated (e.g. Pont et al., 2008a; Spiegel et al., 2009b; Deming et al., 2013).

**Temperature inversion in the solar system** On Earth, the atmosphere is heated from below by solar radiation absorbed at its surface. Air above is heated by convection, with the *troposphere* characterised by a decreasing temperature with height. The *tropopause* marks the start of Earth’s *temperature inversion layer*, or *stratosphere*, caused by a high-level  $\text{O}_3$  layer that absorbs solar ultraviolet radiation and provides heating from above; the absence of stratospheric turbulence results from the



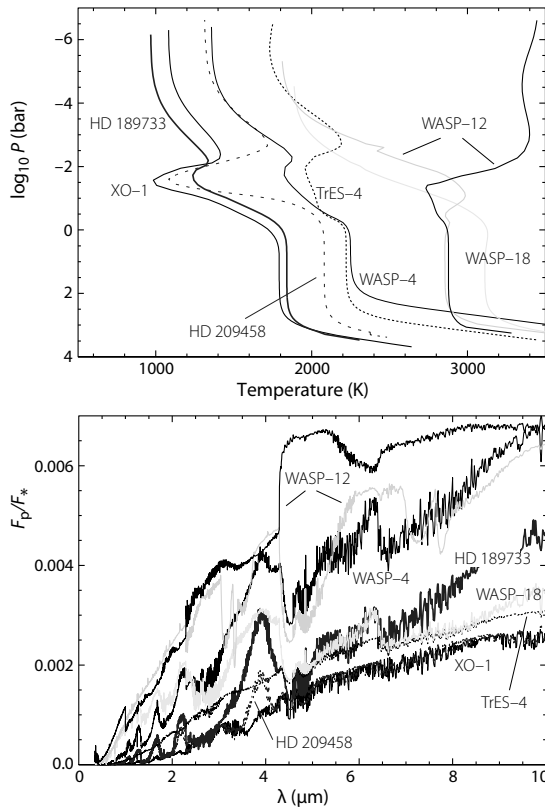


Figure 11.13: Top: model pressure–temperature curves for various transiting giant planets, fitting Spitzer–IRAC data at secondary eclipse. The wide temperature range reflects substellar fluxes as well as extra heating of the upper atmosphere by an absorber often invoked to explain Spitzer–IRAC data, in particular at  $5.8\ \mu\text{m}$ . One model for WASP–12 b includes a temperature inversion (black curve), while the grey model has no inversion, and is depleted in  $\text{H}_2\text{O}$  by a factor 100, and enhanced in  $\text{CH}_4$  and  $\text{CO}$ . Bottom: corresponding planet/star flux ratios from  $0.4\text{--}10\ \mu\text{m}$ . Predicted values span a wide range, while the two WASP–12 b models illustrate uncertainties involved in characterising exoplanet atmospheres. From Burrows (2014b, Figure 3), ©(2014) National Academy of Sciences.

inhibition of convection due to the inverse temperature gradient.  $\text{CH}_4$ -induced hazes and other gases are responsible for the stratospheres of the solar system giants (Figure 11.14).

**Atmospheric circulation** The existence of the detached convective zones for the close-in, highly irradiated atmospheres (Figure 11.7), results in a deep internal heat flow distinct from the thermalised incident radiation. The global temperature distribution is no longer relatively homogeneous, and equator-to-pole and day-night temperature gradients can be large. This is in contrast to the internal heat flow in Jupiter, which is less strongly irradiated, and in which convective transfer results in a relatively isothermal planet at the convective-radiative boundary (Ingersoll & Porco, 1978).

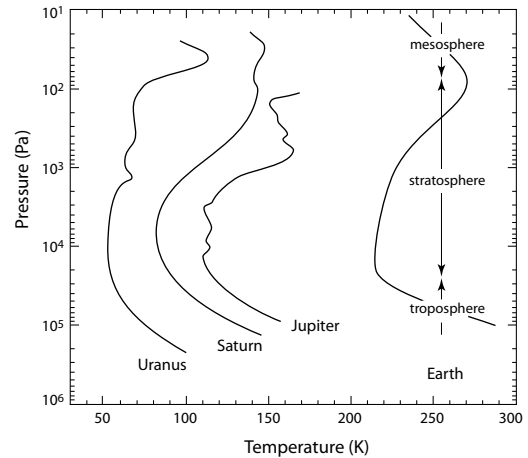


Figure 11.14: Atmospheric pressure–temperature profiles for Earth, Jupiter, Saturn, and Uranus. All have deep adiabatic tropospheres and stratospheres, characterised by temperature inversions (for Earth, between  $\sim 10^2\text{--}10^4$  Pa). Uranus and Jupiter data are from the Voyager radio science occultation experiments, and the Earth profile is from the 1976 US Standard Atmosphere (NASA, 1976). Adapted from Marley (2010, Figure 1), with the Saturn profile provided by Marley (2010, priv. comm.).

The resulting atmospheric circulation in hot Jupiters results in a redistribution of energy by possibly high-velocity atmospheric winds, and thermal emission distributions over the planet surface which depends on the incident energy flux, the atmospheric scale height, the planet rotation rate, and whether it is tidally locked to the star. Further details and predictions of ‘general circulation models’ are given in Section 11.4.2, and related observations are discussed further in §6.24.

**Dependence on initial conditions** Initial conditions for atmospheric evolution models might be based on a large and hot, non-rotating, adiabatic sphere, resulting from core accretion and gas capture according to ‘hot start’ conditions (§10.5.1). Initially this cools and contracts rapidly such that, over a period of several Myr, it might be expected to lose all memory of the starting conditions (Fortney et al., 2008b).

More detailed models, coupling spectroscopic predictions with thermal evolution accretion models (Hubbickj et al., 2005), are described by Marley et al. (2007b) and Fortney et al. (2008b), with predictions of the emergent flux for a range of  $T_{\text{eff}}$  shown in Figure 11.15a.

According to the detailed treatment of gas accretion, ‘cold start’ models begin significantly smaller and colder than the ‘hot start’ models, and initially less luminous by a factor 10–100. Such cool young Jupiters would be 1–6 mag fainter than predicted by ‘hot start’ cooling tracks (Figure 11.15a), with observations therefore providing some diagnostics of the formation mechanism. Significantly, some ‘memory’ of initial conditions appears to persist over evolution times as long as  $\sim 0.1\text{--}1$  Gyr.

**Albedo:** The *albedo* measures the reflectivity of a planet atmosphere resulting from the totality of absorption and scattering processes taking place within it. The two variants of most importance in exoplanet studies are the ‘geometric albedo’, and the ‘Bond albedo’.

The *geometric albedo*,  $p(\lambda)$ , is the ratio of brightness at zero phase (i.e., seen from the star) to that of a fully reflecting, diffusively scattering (Lambertian) flat disk with the same cross section. It is a function of wavelength, and is particularly relevant for the detection of reflected light. It is described further in this context in §6.15.1.

The *Bond albedo*,  $A_B$ , measures the fraction of incident radiation, over all wavelengths, which is scattered. It appears in the expression for the planet’s equilibrium temperature and is described further, along with present observational constraints, in §6.24.

Albedos are strongly influenced by the presence of clouds and *aerosols* (fine solid particles or liquid droplets in suspension). Planets with significant cloud cover are expected to reflect stellar light more strongly (high albedo), hence reducing their infrared luminosity, but increasing the reflected stellar radiation. When only rare species condense, more light is absorbed (low albedo), and the effective temperature and infrared luminosity are higher.

**Chemical composition** Thermodynamic calculations, of the form described in §11.2.2, are used to establish the equilibrium abundances of the elements and chemical species expected to be present in a gas of given elemental composition, temperature, and pressure. Subsequent conditions then determine which condensates form, and which gases are thereby removed such that their spectral signatures disappear.

A table of the principal condensates and gases expected in giants planets of solar composition is given in (Lodders, 2010, Table 2). Determination of the atmospheric composition of Jupiter and Saturn, using these procedures, are described by Fegley & Lodders (1994).

The atmospheric chemistry for giant exoplanets, including the condensation of particular species into clouds, is likely to be broadly similar to that for brown dwarfs of corresponding  $T_{\text{eff}}$ . One difference is the expected presence of deuterated gases (e.g.,  $\text{CH}_3\text{D}$ ,  $\text{HDO}$ ,  $\text{NH}_2\text{D}$ ) in the lower-mass planets, which is depleted by D-burning for the higher mass ( $\geq 13M_J$ ) brown dwarfs.

The reaction pathways of the more abundant reactive elements (notably C, N, and O) influences the chemistry of the less abundant elements, which may form various oxides in cooling gases, depending on the available oxygen. The formation of many molecular gases and condensates is therefore strongly regulated by the C and O chemistry (Lodders & Fegley, 2002; Lodders, 2010).

**Carbon chemistry** The equilibrium distribution of C, over a large range of temperature and pressure, is controlled by the reaction between CO and  $\text{CH}_4$  through



As illustrated in Figure 11.16a, at high temperatures and low pressures (e.g.  $T \gtrsim 1500\text{ K}$ ,  $P \lesssim 10^5\text{ Pa}$ ), CO is the major C-bearing gas, while at lower temperatures and higher pressures,  $\text{CH}_4$  dominates. The latter conditions apply for unirradiated Jupiter-mass planets (including Jupiter), and for separations down  $a \gtrsim 0.1\text{ au}$ , while the former conditions apply at smaller separations.

Predictions are modified for lower temperature formation conditions when chemical equilibrium is not reached. This results in *quenching* of the CO to  $\text{CH}_4$  conversion (viz. stopping or diminishing the chemical reaction), and an overabundance of CO compared to the expected equilibrium values. The effect is seen in Jupiter, Saturn, and Neptune (Fegley & Lodders, 1994), as well as in various T dwarfs (Fegley & Lodders, 1996; Noll et al., 1997a; Saumon et al., 2007; Visscher & Moses, 2011).

**Oxygen chemistry** The major O bearing gases are CO and  $\text{H}_2\text{O}$ . With the presence of SiO and other metal oxides reducing the  $\text{H}_2\text{O}$  abundance, CO becomes the most abundant gas, and the conversion from CO to  $\text{CH}_4$ , which produces equal molar amounts of  $\text{H}_2\text{O}$ , therefore controls the abundance of  $\text{H}_2\text{O}$ .

As a result, the curve of equal abundances of CO and  $\text{H}_2\text{O}$  (Figure 11.16b) is at a similar location in the pressure–temperature diagram to that of the equal CO and  $\text{CH}_4$  abundance (Figure 11.16a). As a consequence, CO again dominates at higher temperatures and lower pressures, while  $\text{H}_2\text{O}$  dominates at lower temperature and higher pressures, as in the case of non-irradiated Jupiter-mass planets.

The abundances of O-bearing gases are further affected by the formation of atmospheric condensates. At high temperatures, oxides and silicates lock up some 20% of the available oxygen, most importantly in forsterite ( $\text{Mg}_2\text{SiO}_4$ ) and enstatite ( $\text{MgSiO}_3$ ). The remaining oxygen at lower temperatures is mainly in  $\text{H}_2\text{O}$  vapour, which condenses into clouds at 200–300 K depending on the pressure–temperature profile.

For a  $1M_J$  planet at 1 au, for example, the pressure–temperature profile coincides with the condensation curve of  $\text{H}_2\text{O}$  ice over a wide range (Figure 11.16b), and spectral signatures of  $\text{H}_2\text{O}$  would be expected. For Jupiter at 5 au in contrast,  $\text{H}_2\text{O}$  clouds lie too deep in the atmosphere to influence the emergent spectra.

**C/O abundance ratio** Variations in C/O ratio, compared to the value of  $\sim 0.5$  in an otherwise solar composition gas, would have observational consequences for the chemistry of gas giant atmospheres because the equilibrium balance between CO,  $\text{CH}_4$ , and  $\text{H}_2\text{O}$  modifies the interior evolution, in turn strongly affecting the resulting emergent spectra (e.g. Fortney et al., 2005, 2006b; Mollière et al., 2015; Venot et al., 2015; Heng et al., 2016; Heng & Tsai, 2016; Espinoza et al., 2017a; He et al., 2017a; Helling et al., 2017).

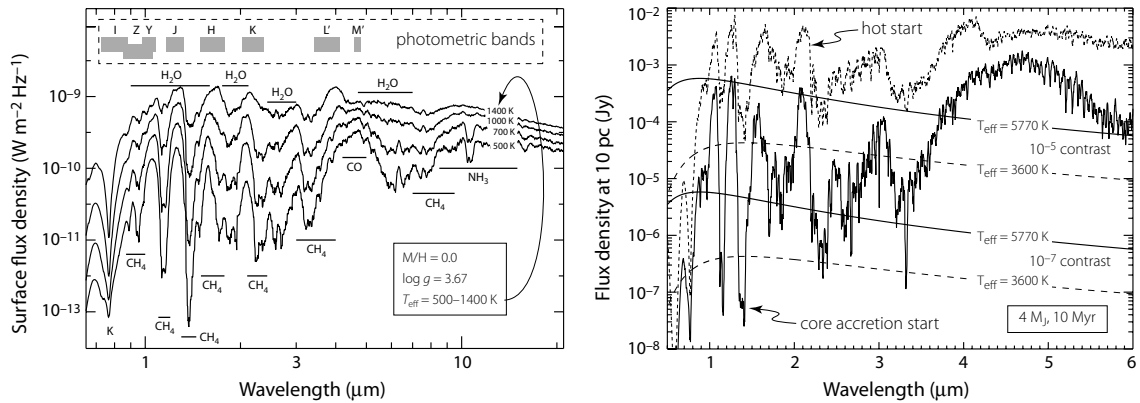


Figure 11.15: Dependence of the predictions of atmospheric models on starting conditions. Left (a): Predicted spectra for cool  $\text{CH}_4$ -dominated atmospheres, of solar metallicity, in the range  $T_{\text{eff}} = 500\text{--}1400 \text{ K}$ , expected for young gas-giant planets based on 'core accretion start' models. Right (b): the flux density at 10 pc illustrates the contrast ratio needed to detect a  $4 M_J$  planet according to the predictions of the 'core accretion start' models (solid lines) compared with the more luminous predictions from the 'hot start' models. Contrast ratios of  $10^{-5}$  and  $10^{-7}$  are shown for solar-type dwarfs with  $T_{\text{eff}} = 5770 \text{ K}$  (solid curve) and M2 dwarfs with  $T_{\text{eff}} = 3600 \text{ K}$  (dashed curve). From Fortney et al. (2008b, Figures 3–4), by permission of IOP Publishing/AAS.

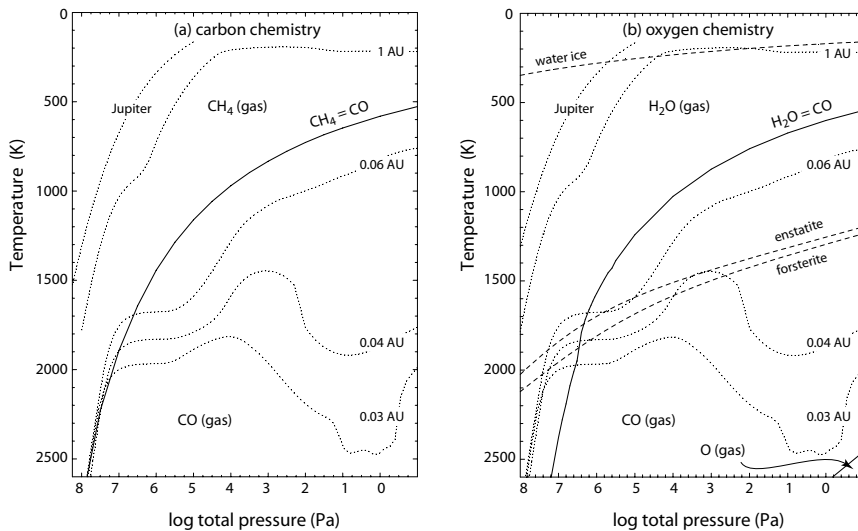


Figure 11.16: (a) The chemistry of carbon in low-mass objects is dominated by  $\text{CO}$  (at high temperatures and low pressures) and  $\text{CH}_4$  (conversely). The solid line is the equal abundance curve for  $\text{CO}$  and  $\text{CH}_4$ , described by Equation 11.24. Dotted lines are pressure-temperature profiles for Jupiter and Jupiter-mass objects at various separations from the host star. (b) Corresponding diagram for the chemistry of oxygen. Temperature and pressure increase to the lower left. From Lodders (2010, Figures 5–6).

Processes which might lead to enhanced exoplanet C/O ratios (e.g., formation in  $\text{H}_2\text{O}$ -depleted or carbonaceous-enriched regions), or diminished C/O ratios (e.g., preferential accretion of  $\text{H}_2\text{O}$  ice), are considered further by Lodders (2010).

WASP-12 is an example of a hot Jupiter with  $\text{C/O} > 1$ , inferred from the observed abundance of  $\text{CH}_4$  and  $\text{CO}$  (Madhusudhan et al., 2011b), placing it a suggested class of *carbon-rich planets*. Detailed photochemical models of the atmospheric chemistry, and paths to forma-

tion, have been described (Madhusudhan et al., 2011c; Madhusudhan, 2012; Kopparapu et al., 2012), with the C/O ratio in this and other hot Jupiters perhaps naturally linked to planet formation near the snow line (Öberg et al., 2011; Brewer et al., 2017).

In a study demonstrating that  $\text{CO}_2$  is subdominant to  $\text{CO}$  and  $\text{H}_2\text{O}$ , Heng & Lyons (2016) suggest setting this as a prior in atmospheric retrieval studies for H-dominated atmospheres, to avoid unphysical inferences on the C/O ratio.

**Disequilibrium due to transport quenching** Early models of extrasolar giant planet atmospheres were based on elemental solar abundances and the assumption of chemical equilibrium (page 578). However, various mechanisms can drive an exoplanet atmosphere out of equilibrium, including the effects of photochemistry and photolysis (page 587), and transport-induced quenching, viz. the stopping or diminishing of chemical reactions as a result of atmospheric circulation.

For HD 209458 b, simulations by Cooper & Showman (2005) suggested a photospheric temperature varying across the surface from 1000–1500 K. At these temperatures, chemical equilibrium models suggest that its atmospheric carbon should be sequestered primarily as CO and CH<sub>4</sub>. However, over the relevant range of atmospheric pressures and temperatures across these irradiated planets, chemical quenching can occur both radially and azimuthally (Cooper & Showman, 2006).

Qualitatively, fluid parcels could attain chemical equilibrium on the planet's day-side, where the temperature is high and the reaction kinetics are fast. Vigorous dynamical motions then carry these equilibrated parcels to the night-side, where they cool rapidly to temperatures at which reactions are too slow to equilibrate. Depending on meteorology and variations of the chemical rates with temperature and pressure, complex lateral CO distributions may result: thus, CO could be abundant at the evening limb, but depleted at the morning limb.

In the solar system, the anomalously high abundance of CO in Jupiter's upper atmosphere is explained by dredge-up of CO-rich gas from the hotter, deeper regions by eddy mixing (Prinn & Barshay, 1977).

**Detailed models** Cooper & Showman (2006) found that in the pressure range  $10^2 - 10^5$  Pa (0.001–1 bar), over 98% of carbon is in CO, even in the cooler regions where CH<sub>4</sub> is more stable thermodynamically. They concluded that the equilibrium picture of CO/CH<sub>4</sub> chemistry is a misconception, that planets 300–500 K cooler than HD 209458 b can also have abundant CO in their upper layers due to disequilibrium effects, and that significantly warmer planets should have no CH<sub>4</sub> in their photospheres unless the C/O ratio is greater than 1.

Other studies have explored disequilibrium effects in further detail, including application to HD 209458, HD 189733, and GJ 436 (e.g. Stevenson et al., 2010; Line et al., 2011; Moses et al., 2011, 2013b; Line & Yung, 2013).

Highly eccentric orbits, such as HD 17156 b, HD 80606 b, HAT-P-2 b and CoRoT-10 b, involve large changes in atmospheric temperature, and associated changes in chemistry, from higher CO at pericentre, to higher CH<sub>4</sub> at apocentre. As the planet atmospheres cool away from pericentre, the chemical time scales for  $\text{CO} \rightleftharpoons \text{CH}_4$  can exceed the orbital and/or vertical mixing time scales, leading to both vertical quenching as well as orbit-induced thermal quenching, i.e. an equilibrium composition achieved near pericentre survives to become a disequilibrium composition at apocentre (Visscher, 2012).

**Other molecules** The variety of compositions found in the gaseous atmospheres of solar system planets suggests that exoplanet atmospheres are likely to be at least

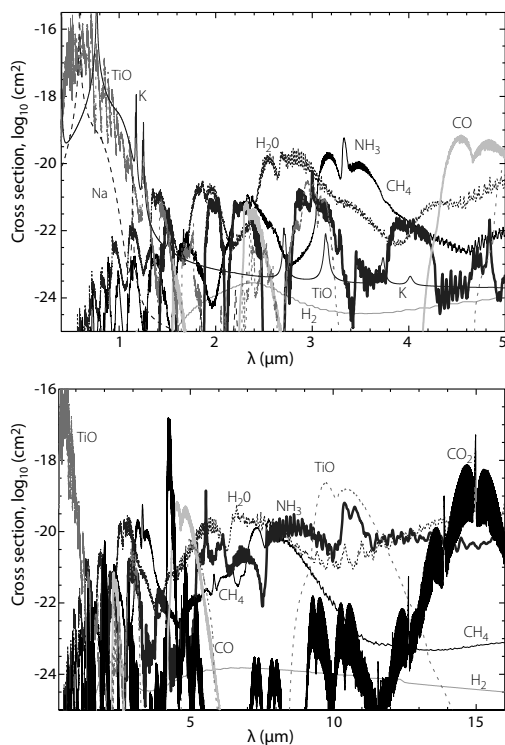


Figure 11.17: Prominent species in (giant) atmospheres, shown as the cross section per molecule or atom versus  $\lambda$  (at 1500 K and  $10^7$  Pa, to better distinguish individual features). Top:  $\lambda = 0.4 - 5 \mu\text{m}$ . Other important molecules are CO<sub>2</sub>, N<sub>2</sub>O, O<sub>2</sub>, and O<sub>3</sub>. Wavelengths of major lines/bands are not significantly temperature- or pressure-dependent, although strengths are. Bottom: extended to 15  $\mu\text{m}$  to highlight the mid-infrared and to include CO<sub>2</sub> (at 296 K and 1 bar). From Burrows (2014b, Figure 1), ©(2014) National Academy of Sciences.

as broad. Generally lower in temperature than stellar atmospheres, planetary atmospheres are dominated by molecules. Though fractionation and differentiation are likely to be involved in their formation, their elemental abundances are expected to reflect the most abundant elements in the Universe. The following summary of predicted compositions is drawn from Burrows (2014b).

For giant exoplanets, as for brown dwarfs, H<sub>2</sub>, He, H<sub>2</sub>O, CO, CH<sub>4</sub>, NH<sub>3</sub>, PH<sub>3</sub>, H<sub>2</sub>S, Na, and K are expected to dominate, with most of the metals sequestered in refractories at depths not easily penetrated spectroscopically. TiO and VO, identified in cool star and hot brown dwarf atmospheres, may exist in the upper atmospheres of some hot Jupiters to heat them by absorption in the optical and create inversions (Fortney et al., 2008a).

For terrestrial planets, other molecules include N<sub>2</sub>, CO<sub>2</sub>, O<sub>2</sub>, O<sub>3</sub>, N<sub>2</sub>O, and HNO<sub>3</sub>, some of which (O<sub>2</sub>, O<sub>3</sub>, and N<sub>2</sub>O, along with the ‘chlorophyll red edge’, §11.8.5) may be biosignatures. Many other compounds can be envisaged, with further complexity due to atmosphere-surface interactions including those evident on Earth.

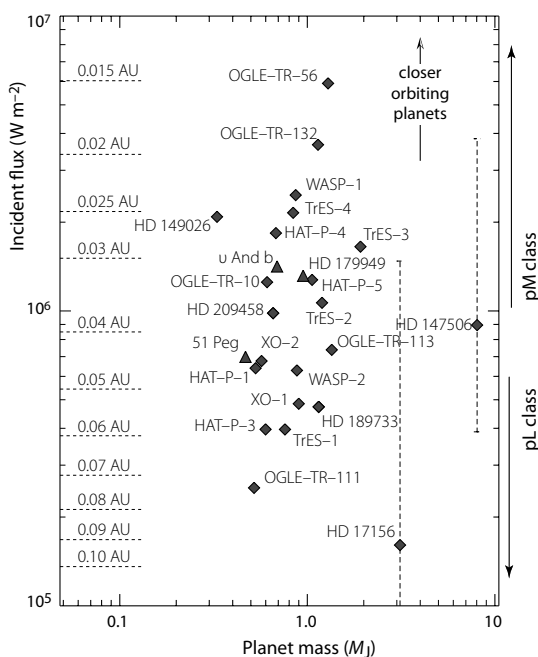


Figure 11.18: Incident flux as a function of planet mass. Labeled lines at left indicate the distance from the Sun at which the planet would intercept this same flux.  $\blacklozenge$  = transiting,  $\blacktriangle$  = non-transiting. Error bars for HD 147506 (HAT-P-2) and HD 17156 indicate the flux range experienced over their eccentric orbit. Separations around  $\sim 0.04$ – $0.05$  au represent the predicted transition region between the classes. From Fortney et al. (2008a, Figure 1), by permission of IOP Publishing/AAS.

A prominent feature for  $O_2$  is the Fraunhofer A-band at  $0.76 \mu\text{m}$ , while the signal feature for  $O_3$  is the band at  $9.6 \mu\text{m}$ . Rayleigh scattering off molecules roughly follows a  $\lambda^{-4}$  dependence, is proportional to the summed product of molecular polarisability and abundance, and is most relevant only in the blue and ultraviolet in reflection. He and  $N_2$  have only weak spectral features.

Figure 11.17 shows gas-phase absorption cross section for  $H_2$ ,  $H_2O$ ,  $CH_4$ ,  $CO$ , Na, K, and  $CO_2$ , species expected to be important in giant exoplanet atmospheres, and also in terrestrial and super-Earths (Sharp & Burrows, 2007; Kratz, 2008; Rothman et al., 2008).

Strong  $H_2O$  features are ubiquitous, at  $0.94$ ,  $1.0$ ,  $1.2$ ,  $1.4$ ,  $1.9$ ,  $2.6$ , and  $5$ – $7 \mu\text{m}$ . These define the *I*, *Z*, *J*, *H*, *K*, and *M* bands for near-infrared ground-based astronomy.  $CH_4$  has important features at  $0.89$ ,  $1.0$ ,  $1.17$ ,  $1.4$ ,  $1.7$ ,  $2.2$ ,  $3.3$ , and  $7.8 \mu\text{m}$ .  $CO$  is prominent at  $2.3$  and  $4.5 \mu\text{m}$ , while  $CO_2$  has diagnostic features near  $2.1$ ,  $4.3$ , and  $15 \mu\text{m}$ .  $NH_3$  has many features, with that at  $10.5 \mu\text{m}$  particularly prominent.

Molecular  $H_2$  has no permanent dipole, but one can be induced by collisions at high pressure, resulting in undulations from  $\sim 2.2$ – $20 \mu\text{m}$  that is seen in Jupiter and Saturn, as well as in brown dwarfs.

**Atmospheric classification:** Various suggestions for the classification of gas giant atmospheres have been made, although predictions are affected by factors such as circulation and haze.

**Class I–V:** Sudarsky et al. (2000, 2003) assigned gas giants to five classes, with temperature-dependent atmospheric properties. In the solar system, only Jupiter and Saturn fall within this proposed classification, and both are Class I. Planets of classes IV and V represent the hot Jupiters.

- Class I,  $NH_3$  clouds,  $T_{eq} \lesssim 150$  K (cool star or distant orbit).  $A_B \sim 0.57$  for a class I planet around a Sun-like star. Candidates include 47 UMa c/d, *v* And e, and 55 Cnc d.
- Class II,  $H_2O$  clouds,  $T_{eq} \sim 150$ – $250$  K. For a class II planet around a Sun-like star  $A_B \sim 0.81$ . Atmospheres would consist mainly of  $H_2$  and H-rich molecules such as  $CH_4$ . Candidates include 55 Cnc f, 47 UMa b, GJ 876 b/c, Kepler-86 b, Kepler-90 h, and HD 10180 g.
- Class III, cloudless,  $T_{eq} \sim 350$ – $800$  K (Mercury-like orbits): planets would not form global cloud cover due to absence of suitable condensates. They would appear as featureless blue globes because of Rayleigh scattering and  $CH_4$  absorption.  $A_B \sim 0.12$  for a class III planet around a Sun-like star. For  $T_{eq} \geq 700$  K, sulphides and chlorides might provide cirrus-like clouds. Candidates include *v* And c, 55 Cnc c, CoRoT-9 b, HD 18742 b, HD 37124 b, HD 178911 b, HD 205739 b, and Kepler-89 e.
- Class IV, alkali metals,  $T_{eq} \geq 900$  K: CO becomes the dominant C-molecule. Alkali metals increase substantially, and spectral lines of Na and K are prominent. Cloud decks of silicates and Fe form deep in their atmospheres, without affecting their spectrum. Low Bond albedo results from strong absorption by alkali metals, with  $A_B \sim 0.03$  for a class IV planet around a Sun-like star. Candidates include HD 209458 b (1300 K) and HD 189733 b (920–1200 K).
- Class V, silicate clouds,  $T_{eq} \geq 1400$  K: for the very hottest gas giants, silicate and Fe cloud decks lie high up in the atmosphere.  $A_B \sim 0.55$  for a class V planet around a Sun-like. The planet may glow red from thermal radiation, but the reflected light generally overwhelms thermal radiation. Candidates include 51 Peg b and HAT-P-11 b.

**Classes pM/pL:** Burrows et al. (2007b) and Fortney et al. (2008a) suggested that hot Jupiters fall into two reasonably distinct categories, characterised by stellar incident flux and its effect on TiO and VO opacities (Hubeny et al., 2003). They referred to them as ‘pM-class’ and ‘pL-class’, in analogy with the M- and L-type brown dwarfs (Figure 11.18).

- the hotter pM-class are characterised by high incident stellar flux, resulting in gas-phase TiO/VO (Burrows et al., 2007b; Fortney et al., 2008a; Burrows et al., 2008a) or non-equilibrium photochemistry. The high-altitude absorber results in a temperature inversion. They are expected to appear bright in the infrared, and to show molecular bands in emission. Examples include HAT-P-7, HD 149026, HD 209458, KELT-16, TrES-4, WASP-1, and XO-2.
- the cooler pL-class have atmospheres receiving less stellar flux (e.g. WASP-43). Titanium and vanadium are condensed out, the incident flux is absorbed deeper in the atmosphere, and no temperature inversion is generated. Energy absorption deeper in the atmosphere leads to greater energy redistribution, and so cooler day-sides, warmer night-sides, and strong advecting jet flows leading to large phase shifts in their thermal emission light curves.

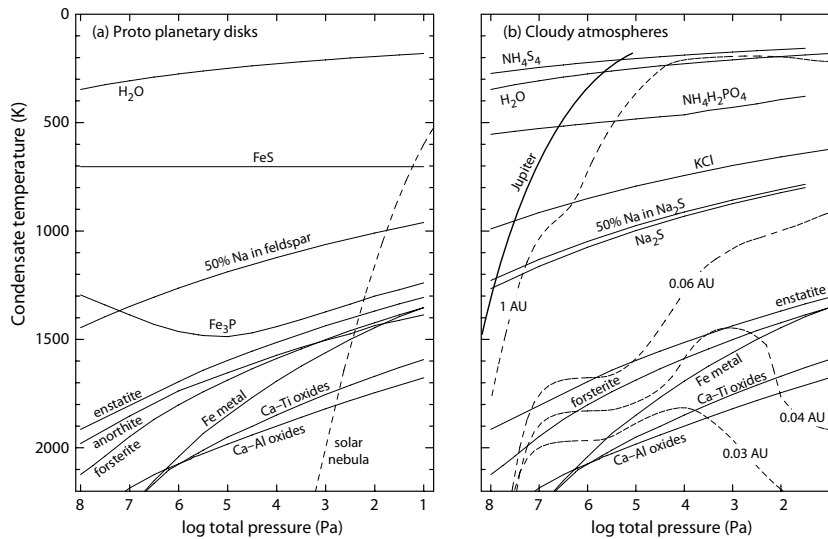


Figure 11.19: Condensates predicted according to the importance of gravitational settling: (a) in low-gravity environments such as protoplanetary disks, high-temperature condensates (e.g. Fe) remain dispersed within the gas, and can continue to react with it to form secondary condensates at lower temperature (e.g. FeS); (b) in high-gravity environments such as planetary atmospheres, the condensates settle into cloud layers and are removed from further reactions. There are no secondary condensates, and other species condense at lower temperature. From Lodders (2010, Figure 7).

**Condensate clouds and rainout** The abundances of species predicted by thermodynamic equilibrium calculations are affected by the formation of condensates within the atmosphere. For a gas parcel rising and cooling adiabatically from a hot deep interior in which all gases present are well mixed, a point is reached where a condensable species condenses, and a cloud base is formed. The first species to condense, at the lowest layers, are the highly refractory oxides such as perovskite ( $\text{CaTiO}_3$ ) and corundum ( $\text{Al}_2\text{O}_3$ ), followed by various magnesium silicates, and so on through species of progressively lower volatility. As the more refractory species condense out with decreasing temperature, those species are depleted, and at least partially removed from further gaseous reactions.

Detailed results of the condensation process differ according to whether the medium is strongly gravitationally stratified (such as in exoplanet atmospheres), or exists instead as a low-gravity environment (such as in protoplanetary disks). In the former case, condensates settle due to gravity and form cloud layers, and thus are no longer available for reaction with the cooler gases at higher altitudes. In the latter case, the condensates can remain dispersed throughout the gas, with secondary reactions still possible (Figure 11.19).

The consideration of condensing cloud layers, or *rainout*, was originally developed for the modeling of the solar system giants (Lewis, 1969; Barshay & Lewis, 1978). It was subsequently applied to models of cool dwarfs (Lodders, 1999), and to brown dwarfs and giant

exoplanets (Burrows & Sharp, 1999). Inclusion of rainout is required for the accurate spectral modeling of brown dwarfs and the solar system giant planets (Fegley & Lodders, 1994; Burrows et al., 2002; Marley et al., 2002).

Expected cloud compositions for the gravitationally-settled models follow from a consideration of the abundances and volatility of the various species. The broad range of estimated gas giant equilibrium temperatures, from around 200 K in the case of 47 UMa to around 1500 K in the case of  $\tau$  Boo, signifies planetary atmospheres very different from each other, and from the planetary atmospheres in the solar system, with consequences for their composition and their spectral appearance (Figure 11.20).

**Condensates versus temperature** Following Lodders (2010), the most abundant rock-forming elements Mg, Si, and Fe produce clouds of forsterite ( $\text{Mg}_2\text{SiO}_4$ ), enstatite ( $\text{MgSiO}_3$ ), and liquid iron respectively. Less abundant rock-forming elements (Ca, Al, Ti, Mn, Cr) result in less massive clouds. Lower volatility condensates composed of O, S, N and C form at  $T \lesssim 200$  K.

Even for giant planets with low-temperature upper atmospheres, which are expected to have massive ice-cloud layers of  $\text{H}_2\text{O}$  (solid or liquid),  $\text{NH}_3$ , and  $\text{CH}_4$ , their deeper atmospheric layers will host clouds covering the full sequence of more refractory species. Although these deep layers are not seen directly in Jupiter, for example, the presence of iron clouds is inferred from the presence of FeS gas (Niemann et al., 1998).

Heated gas giants are dominated by TiO and VO bands in the optical, and  $\text{H}_2\text{O}$ , CO, and FeH bands in the infrared. Refractory ceramics such as corundum ( $\text{Al}_2\text{O}_3$ ), Ca-aluminates, and Ca-titanates appear near 1800–2200 K, leading to the disappearance of the bands TiO and VO. For the closest (hottest)

planets, temperatures are too high for the condensation of the refractory ceramics, and TiO and VO remain.

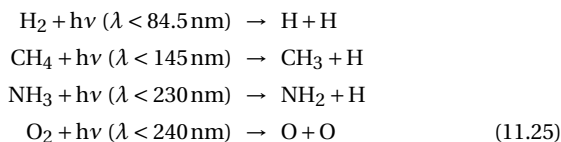
At 1200–1500 K, depending on pressure, Fe condensation, Cr/Cr<sub>2</sub>O<sub>3</sub> condensation, and Mg-silicate (Mg<sub>2</sub>SiO<sub>4</sub>/MgSiO<sub>3</sub>) condensation consume the Fe, Cr, Mg, and Si gases, removing all of the major rock-forming elements from the atmosphere above the MgSiO<sub>3</sub> cloud. Lines of monatomic alkali metals (K, Na, Cs, Rb) will persist to lower temperatures, gradually converting to NaCl, KCl, oxides, hydroxides, and hydrides, before being removed as sulphide and halide condensates.

Decreasing temperatures, leading to the disappearance of CO and the appearance of CH<sub>4</sub> (Figure 11.16), results in CH<sub>4</sub> absorption bands at 1.6, 2.2, and 3.3 μm. Thereafter, CH<sub>4</sub>, H<sub>2</sub>O, and NH<sub>3</sub> characterise the cooler objects until the condensation of H<sub>2</sub>O into liquid or solid form, and the condensation of NH<sub>3</sub> into solid form, leaves only CH<sub>4</sub> in an otherwise H/He-rich atmosphere. Condensation of CH<sub>4</sub> only occurs at very low temperatures,  $T \lesssim 50$  K. It is the high-level NH<sub>3</sub> clouds, along with various by-products of photolytic dissociation, that reflect sunlight back from Jupiter.

**Photochemistry and photolysis** The term *photochemistry* refers to all aspects of the interaction between light and atoms or molecules, including photoionisation and photoevaporation. *Photolysis* (or photolytic dissociation) concerns more specifically the breakdown of molecules as a result of photon interactions. Atmospheric photochemistry is driven by the more energetic stellar photons (ultraviolet, extreme ultraviolet and, in principle, X-rays and γ-rays) and, in a more liberal use of the term, energetic electrons.

Photochemistry can alter the stratospheric composition of atmospheres by enhancing or depleting various species. Zonal winds can transport photolytically produced species from the day-side to the night-side. More generally, photolytic dissociation results in photochemical products which can contribute to radiative transfer, participate in further chemical reactions, and accelerate hydrodynamic escape (Rybicki, 2006).

Whether a particular reaction is important in any given atmosphere depends on the photon penetration depth, and whether it reaches the relevant gaseous or condensable species. Dissociation due to ultraviolet radiation is usually relevant only high in the atmosphere, before the bulk of the radiation is absorbed or scattered back to space (Yung & Demore, 1999). As examples



with the latter being the first step in the formation of ozone (O<sub>3</sub>) in Earth's stratosphere.

The complex reaction pathways and photochemical products for solar system atmospheres are detailed by Strobel (2005). In the gas giants, CH<sub>4</sub> photolysis leads to the production of heavy hydrocarbons. Molecular

species such as H<sub>2</sub>O, H<sub>2</sub>S, and NH<sub>3</sub> are condensed below other cloud layers, and so are unavailable for photodissociation. In hot Jupiter atmospheres, in contrast, these species are gaseous, and no longer protected (Marley, 1998; Liang et al., 2004). S and N compounds may be important in hot Jupiter haze-producing photochemistry (Marley et al., 2007a). Photolytic compounds including CO<sub>2</sub>, HCN, and C<sub>2</sub>H<sub>6</sub> may be present in GJ 229 B and, by analogy, in H<sub>2</sub>O-bearing gas giant atmospheres (Troyer et al., 2007).

**Photoionisation** Photoionisation may produce high e<sup>-</sup> densities in the middle atmospheres of hot Jupiters, affecting transit depths in alkali atoms (Ionov et al., 2014; Lavvas et al., 2014).

**Terrestrial planets** For terrestrial planets, photolytic dissociation may be a significant complication in characterising atmospheres based on their colours (e.g. Pallé et al., 2008b). An Earth-like planet with a higher CH<sub>4</sub> abundance may be enveloped in a photochemical haze, and unrecognisable as an ocean- or vegetation-dominated planet (Zahnle, 2008). On the other hand, photodissociation may make H<sub>2</sub>O in terrestrial or ocean planet atmospheres detectable through ultraviolet absorption in the Lyman lines of atomic hydrogen (Jura, 2004).

**Photochemical transport** Various 1d and 3d photochemical transport models have been used to explore the compositions of • hot Jupiters (Liang et al., 2003, 2004; Cooper & Showman, 2005; Zahnle et al., 2009; Line et al., 2010; Moses et al., 2011; Visscher & Moses, 2011; Agúndez et al., 2012; Kopparapu et al., 2012; Venot et al., 2012; Kempton et al., 2014; Moses & Poppe, 2017), • hot Neptunes (Line et al., 2011; Moses et al., 2013b), and • super-Earths (Miller-Ricci Kempton et al., 2012; Hu et al., 2012b, 2013; Hu & Seager, 2014).

These models have been used to argue, for example, that H<sub>2</sub>S and SO<sub>2</sub> are chemically short-lived in virtually all types of (H<sub>2</sub>, N<sub>2</sub>, and CO<sub>2</sub>) atmospheres on terrestrial exoplanets. This implies that the direct detection of surface sulphur emission is unlikely, as surface emission rates would need to be extremely high (more than 1000 times Earth's volcanic sulphur emission) for them to build up to a detectable level.

In cool atmospheres ( $T \leq 1200$  K), non-equilibrium mechanisms become increasingly more important as chemical reaction time scales increase. Jovian-like atmospheres can accordingly be divided vertically into three chemical regimes (Line & Yung, 2013): (a) in the deep atmosphere where temperatures and pressures are high, chemical reaction time scales are short, and compositions achieve thermochemical equilibrium; (b) higher in the atmosphere, at lower pressures and temperatures, reaction times decrease until they are equal to the vertical transport time scale, quenching the abundances, and with vertical mixing tending to smooth out the profiles; (c) at even higher altitudes, ultraviolet photons can disrupt stable molecules and alter the upper atmospheric composition.

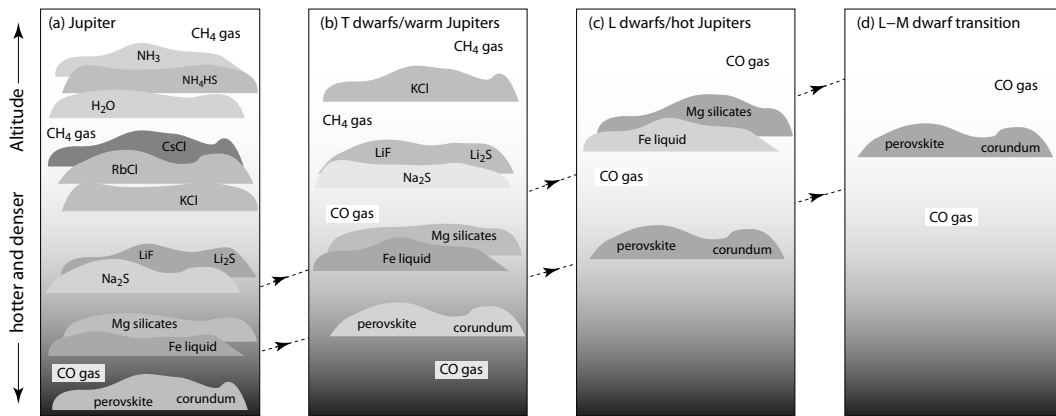


Figure 11.20: Schematic of cloud-like condensations versus altitude expected in exoplanets and brown dwarfs of various temperatures: (a) Jupiter; (b) T dwarfs and Jupiters too warm for  $\text{H}_2\text{O}$  clouds to form; (c) L dwarfs and hot Jupiters; (d) L–M dwarf transition objects. The overall structures are similar, but cloud levels are higher in the warmer atmospheres for the refractory species, while the more volatile species may not condense at all as the temperature increases. From Lodders (2004a, Figure 1).

**Clouds or hazes?** Two distinct mechanisms can generate aerosols in hot Jupiter and other atmospheres (box, page 589): clouds are formed by direct condensation of atmospheric gases (and are typically supported in an atmosphere by turbulent mixing), and hazes are formed at high altitudes via chemical reaction pathways initiated by ultraviolet photolysis. Both result in the formation of solid or liquid aerosols, and both have similar observational consequences, viz. weak absorption features, and strong scattering signatures in transmission spectra.

Assembled in a grain, such aggregations can, depending on particle size and observation wavelength, respond coherently to light, such that low mass density can translate into a large optical depth, with the consequence that trace species can be disproportionately prominent (e.g. Marley et al., 1999, 2013; Burrows, 2014b). In addition, with a spectrum of particle sizes and enhanced line-broadening in the grain, their absorption and scattering cross sections can have a continuum character and veil a wide spectral range. The result can be partial (or complete) suppression of the gas-phase spectral features. To properly handle their effects requires knowledge of the condensate species, grain size and shape distributions, the complex index of refraction, and their spatial distribution.

The presence of clouds and hazes, widely demonstrated by transmission spectroscopy, typically results in a flattening of spectral features due to the inability of stellar photons to reach atmospheric depths below the cloud and haze layers (Gibson et al., 2012a, 2013a; Deming et al., 2013; Jordán et al., 2013; Mandell et al., 2013; Sing et al., 2013; Chen et al., 2014c; Schlawin et al., 2014; Wilkins et al., 2014; Fukui et al., 2014; Mallonn & Strassmeier, 2016). Flat transmission spectra have been in exoplanets of different sizes, temperatures, and stellar

irradiation levels (e.g. Crossfield et al., 2013; Kreidberg et al., 2014b; Knutson et al., 2014a,b; Sing et al., 2016).

Clouds and hazes have also been inferred from optical phase curves, where high albedos have been attributed to reflective clouds (e.g. Demory et al., 2013a). Clouds have also been invoked to explain spectra of directly imaged exoplanets, including HR 8799,  $\beta$  Pic, and 51 Eri (Barman et al., 2011a; Madhusudhan et al., 2011a; Marley et al., 2012; Currie et al., 2014b; Skemer et al., 2014b; Chilcote et al., 2015; Macintosh et al., 2015).

The composition and vertical structure of atmospheric aerosols is relevant to an understanding of their reflected light (e.g. Marley et al., 2013). As examples, cloudless gas giants are expected to be relatively bright at blue wavelengths but dark in the red and near infrared where molecular absorption dominates over Rayleigh scattering, while cloudy planets, by scattering more photons before they can be absorbed, can be much brighter (Marley et al., 1999; Sudarsky et al., 2000). Similarly, there are large differences in the reflected light spectra of super-Earths depending on whether the planet is cloudy or hazy, and the kind of aerosols present (Morley et al., 2015; Charnay et al., 2015b).

Cooler planets with KCl and  $\text{H}_2\text{O}$  clouds may be more reflective than clear planets in the near-infrared, while ZnS clouds, forming at similar temperatures, are more absorbing. Planets with complex hydrocarbon ‘soot’ hazes could be very dark, whereas tholin-type hazes are dark at bluer wavelengths but more reflective at the red end. Sulphur haze will mask the molecular signatures of  $\text{CH}_4$  and  $\text{H}_2\text{O}$ , requiring observations shortward of  $0.4 \mu\text{m}$  to discriminate between any other high-reflectivity, high-altitude scatterer (Gao et al., 2017).

The reflectivity of clouds and hazes also impacts the amount of compositional information that can be re-



**Clouds and hazes:** Clouds and hazes are both *aerosols* (a contraction of *aero-solution*), viz. colloidal suspensions of fine solid particles or liquid droplets in a gas (e.g. Heng et al., 2012; Kempton et al., 2017a). *Clouds* are equilibrium condensates, layers of enhanced optical depth caused by chemical species condensing out of their gaseous forms. Formed at the pressure level where their condensation curves intersect the atmospheric pressure–temperature profile, they are of thermodynamic origin. *Hazes* are a distinct opacity source of non-thermodynamic origin, either quasi-uniform throughout the atmosphere, or at a pressure level unrelated to a particular condensation curve.

Examples of clouds: H<sub>2</sub>O clouds on Earth, and NH<sub>3</sub> and CH<sub>4</sub> clouds in the atmospheres of Jupiter and Saturn have been observed in detail, while in L dwarfs, clouds of Mg–Fe silicates (notably the end-member enstatite, MgSiO<sub>3</sub>) are inferred from their red infrared colours (Sudarsky et al., 2000). With increasing temperatures, clouds in exoplanet atmospheres are also predicted to include sulphides (including Na<sub>2</sub>S), chlorides (including KCl), silicates, TiO and VO (e.g. Burrows et al., 2003b; Sudarsky et al., 2005).

Examples of hazes: At  $T_{\text{eq}} \lesssim 1100$  K, CH<sub>4</sub> is the dominant C-molecule for an equilibrium atmosphere. Methane photolysis results in the formation of C<sub>2</sub>H<sub>2</sub> (acetylene) and HCN in the upper atmosphere, which are expected to lead via polymerisation to ‘soot’-type hazes (Bar-Nun et al., 1988; Sudarsky et al., 2000; Morley et al., 2015).

*Tholins*, from the Greek for ‘hazy’ or ‘muddy’, describe a heterogeneous range of organic compounds synthesised in Miller–Urey-type experiments by Sagan & Khare (1979). Formed by the ultraviolet photolysis of molecules such as CO<sub>2</sub>, CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, H<sub>2</sub>O, and NH<sub>3</sub>, they are thought to comprise Titan’s hazes (Khare et al., 1984; Burrows, 2014b).

At higher metallicity, H<sub>2</sub>S is the dominant equilibrium reservoir of atmospheric sulphur for temperate Jupiter-masses ( $T_{\text{eq}} \sim 250 - 700$  K), with various haze-production pathways (e.g. Gao et al., 2017). In reducing atmospheres, H<sub>2</sub>S photolysis can result in elemental sulphur (S<sub>8</sub>) between  $P \sim 1 - 10^4$  Pa, which, if cool enough, will condense to form a haze (Zahnle et al., 2016). Sulphur aerosols have been proposed for the Venusian atmosphere, especially in regions depleted in oxidants (Toon et al., 1982; Zhang et al., 2012), while terrestrial planets with H<sub>2</sub>-dominated atmospheres could be enveloped in sulphur hazes resulting from volcanic H<sub>2</sub>S outgassing (Hu et al., 2013).

In oxidising atmospheres, SO<sub>2</sub>, OCS, and H<sub>2</sub>S can be transformed into sulphuric acid through photolysis and hydrolysis. Condensation of H<sub>2</sub>SO<sub>4</sub> can then form clouds and hazes, as in the global cloud deck of Venus (Hansen & Hovenier, 1974), and the Junge layer in Earth’s upper stratosphere (Junge, 1963; Turco et al., 1982).

trieved from direct imaging, as reflected light is only able to sample the atmosphere above the cloud or haze deck. If the deck is at high altitudes, then the column optical depth of absorbing gases that direct imaging can sample is small, reducing the prominence of their spectral features in their reflected light spectra, while if the cloud/haze is absorbing, then very few photons can sample the chemical composition of the atmosphere and escape (Marley et al., 1999; Sudarsky et al., 2000).

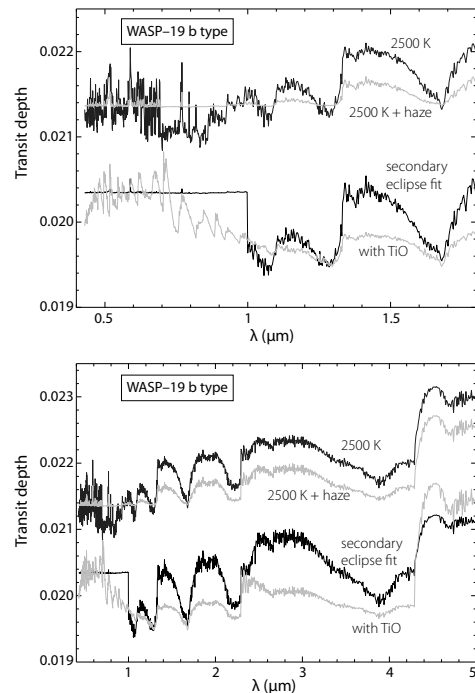


Figure 11.21: Model transit depths at 0.4–1.8  $\mu\text{m}$  (top) and 0.4–5  $\mu\text{m}$  (bottom) for an irradiated WASP-19 b-like planet. Lower grey curves are day-side models with atmospheric TiO, and redistribution parameter  $f = 0.3$ . Lower black curves include an ‘extra absorber’ at altitude (opacity  $0.05 \text{ cm}^2 \text{ g}^{-1}$  from 0.4–1.0  $\mu\text{m}$ ) to fit the Spitzer–IRAC secondary eclipse data. Both upper models have isothermal atmospheres at 2500 K, with the flatter grey model having uniform haze with opacity  $0.01 \text{ cm}^2 \text{ g}^{-1}$ . For clarity, the latter two are shifted from the former two. In all models, H<sub>2</sub>O features are most prominent. Variations with  $\lambda$  are typically  $< 10^{-3}$ . From Burrows (2014b, Figure 2), ©(2014) National Academy of Sciences.

**Model complexities** It is generally not straightforward to determine whether the aerosols blocking the stellar photons are part of a cloud, or part of a haze. Spectroscopic determination of aerosol compositions are complicated because signatures are often only weakly wavelength dependent, are degenerate with properties such as particle size and distribution, and are currently only barely detectable (if at all) with current observational facilities. The complex chemistry, multiple formation pathways, and lack of easily identifiable spectral features make it challenging to constrain their key properties.

Patchy clouds can mimic high mean molecular weight cloud-free atmospheres (Line & Parmentier, 2016), while the wavelength-dependent opacity (grey versus Rayleigh scattering) is independent of formation mechanism.

Even in the solar system, there are cases where hazes have been inferred, but where the species responsible are either unknown, or poorly modeled. Thus a thick haze envelops the atmosphere of Titan, and there is a trace absorber in the blue that makes Jupiter and Saturn redder than Neptune or Uranus. In the case of Jupiter, the factor of two suppression in its reflected blue flux is possibly due to trace species at parts in  $10^{10}$  (Sudarsky et al., 2000; Burrows, 2014b). Such an unknown extra optical absorber has been invoked, at altitude, to explain the

inversions and over-hot atmospheres inferred from secondary eclipse spectra of some hot Jupiters (Burrows et al., 2007b).

In general, scattering is important only in reflection and transit spectra, not in emission, and is most prominent for hazes and clouds. Longward of the ultraviolet, clouds are necessary to give planets any appreciable reflection albedo above  $\sim 1\%$  (Sudarsky et al., 2000). Also, in reflection, clouds or ultraviolet/blue Rayleigh scattering can yield highly polarised fluxes, suggesting that polarisation might be a useful ancillary diagnostic (Madhusudhan & Burrows, 2012, see also §6.17).

Unlike for gas species, for many realisations of likely hazes or clouds, the scattering albedo can be either high or low, depending on species and wavelength range. This suggests that reflection spectra can be dominated by the effects of such layers, and that transit spectra can be affected by particulate scattering (as opposed to only absorption).

To underline the possible range of models that can be fitted to existing data, Figure 11.21 shows representative theoretical transit spectra from 0.4 to 5.0  $\mu\text{m}$  for a WASP-19 b-like planet from Burrows (2014b). The models include isothermal atmospheres at  $T = 2500\text{ K}$ , with and without a uniform grey haze with an opacity of  $0.01\text{ cm}^2\text{ g}^{-1}$ , a model that attempts to fit its Spitzer-IRAC data at secondary eclipse (Anderson et al., 2013) with an unknown ‘extra absorber’ at altitude of constant optical opacity  $0.05\text{ cm}^2\text{ g}^{-1}$  (from 0.4 to 1.0  $\mu\text{m}$ ), and a similar model employing TiO as the extra absorber. The transit depth is  $\sim 2\%$ , while the variation due to the presence of H<sub>2</sub>O bands is approximately one part in a thousand.

**Distinguishing hazy, cloudy and clear atmospheres** Other techniques for distinguishing between hazy, cloudy and clear atmospheres have been suggested. These include the measurement of absorption wing steepness, or through comparison of the depths of multiple absorption bands (Benneke & Seager, 2013). Another suggestion is to exploit the refraction signatures in a transit light curve pre-ingress and post-egress (§6.14.11).

**Single hemisphere aerosols** The most highly irradiated hot Jupiters, with  $T_{\text{eq}} \geq 2000\text{ K}$ , have day-sides that are too hot for cloud condensation. As a result, clouds are expected to form only on their night-side, or downwind of the anti-stellar point on the cooler (morning) terminator (seen as the leading limb during transit), but not on the hotter evening terminator (Parmentier et al., 2016; Kempton et al., 2017a). Conversely, haze-forming photochemistry can only occur on a tidally-locked planet’s day-side where the stellar ultraviolet flux initiates the photolysis reaction pathway, and will be carried downwind by atmospheric dynamics to the evening terminator (seen as the planet’s trailing limb during transit).

Occurrence of these ‘single-hemisphere aerosols’ affects the expected shape of the ingress and egress transit light curves (e.g. Line & Parmentier, 2016; von Paris et al., 2016a). Similarly, because opposite limbs are expected to be impacted by different types of aerosols, ingress and egress spectra, which primarily probe opposing sides of the planet, should reveal the dominant formation mechanism (Kempton et al., 2017a).

Evidence of night-side and/or morning terminator clouds has been reported in hot Jupiter phase curves at both optical (Demory et al., 2013a; Esteves et al., 2015; Hu et al., 2015a; Shporer & Hu, 2015) and infrared wavelengths (Stevenson et al., 2014d; Kataria et al., 2015; Stevenson et al., 2017). At the same time, reaction networks leading to haze formation appear to be most efficient for cooler planets (e.g. Moses, 2014; Zahnle et al., 2016). Accordingly, night-side clouds may be a favoured aerosol production pathway for highly irradiated hot Jupiters.

As a consequence of the formation pathways and the atmospheric circulation, Kempton et al. (2017a) have argued that the ingress transmission spectrum, which primarily probes the leading limb, is a diagnostic of clouds, while the egress spectrum diagnoses haze (see their Figure 1). By differencing the two, they suggest that observations with JWST (and potentially HST) should be able to distinguish between clouds and haze for many known highly irradiated hot Jupiters. Their 10 favoured candidates, based on the expected transmission signal scaling as  $R_p H / R_*^2$  (Equation 6.154), includes WASP-121 b, which has been shown to have H<sub>2</sub>O-features in its transmission spectrum, along with strong hints of TiO, VO, and possibly FeH absorption (Evans et al., 2016c).

**Molecular lines and opacities** Detailed characterisation of exoplanet atmospheres is a challenging problem confronted by their great complexity (Burrows, 2014b). Compared with stars, whose atmospheres comprise atoms and their ions, and whose principle properties are determined once their mass and metallicity is known, planets have molecular atmospheres with a wide range of compositions, reflecting their formation environment, accretion processes, complicated photochemistry induced by intense stellar irradiation, and even their geophysical histories. Anisotropic stellar irradiation and rotation break underlying symmetry, with clouds and hazes introducing multiple complexities, still unresolved even for Earth.

Molecular spectra are considerably more complicated than those of atoms, with  $10^2 - 10^3$  times more lines. While the understanding of stellar atmospheres is still challenged by uncertainties in oscillator strengths and equilibrium issues, the spectroscopic databases for molecules, and particularly at the high temperatures (500–3500 K) experienced by close-in transiting planets, are considered quite incomplete, and many of the relevant collisional excitation rates and opacities remain poorly characterised (box, page 570).

**Rayleigh scattering** An important source of opacity at short visible and near-ultraviolet wavelengths is (elastic) Rayleigh scattering of light by molecules. Spectral regions so dominated can be used to determine the atmospheric scale height, through changes in the effective planet radius with wavelength (e.g. Lecavelier des Etangs et al., 2008a; Benneke & Seager, 2012; Howe & Burrows, 2012). Since the spectral dependence of Rayleigh scattering cross sections are well known, the Rayleigh slope can be used to discriminate between various bulk atmospheric composition, provided that the atmosphere is relatively clear of hazes or clouds (box, page 589).

In the presence of extended vertical hazes, the transmission spectrum will instead carry the signature of the optical properties of the haze (e.g. Howe & Burrows, 2012; Robinson et al., 2014b; Wakeford & Sing, 2015). Conclusions are also modified by the effects of refraction (§6.14.11). Either way, the slope provides an important constraint on atmospheric properties.

Rayleigh scattering has been detected in a number of cases, including (chronologically) HD 209458 (Knutson et al., 2007c; Sing et al., 2008b), HD 189733 (Pont et al., 2008a), HAT-P-5 (Southworth et al., 2012c), GJ 3470 (Nascimbeni et al., 2013b), WASP-12 (Sing et al., 2013), WASP-6 (Jordán et al., 2013; Nikolov et al., 2015), Qatar-2 (Mancini et al., 2014c), WASP-31 (Sing et al., 2015), and WASP-103 (Southworth et al., 2015a).

**Raman scattering** Raman scattering is a weaker process resulting from *inelastic* scattering off molecules, such as H<sub>2</sub> and N<sub>2</sub>, excited to higher vibrational or rotational energy levels. It leaves a number of distinct signatures imprinted in the reflected light (including frequency change of the scattered photons) and the planet's geometric albedo that could, if detected, be used to probe the physical conditions and the chemical composition of the atmosphere (Oklopčić et al., 2016). Detecting Raman features in nearby hot exoplanets may be possible with the next generation of 30-m ground-based telescopes.

**Lightning** As quantified from extensive solar system observations, lightning (atmospheric electrical discharge) is a tracer of atmospheric convection, cloud formation and ionisation, and may be significant for the formation of prebiotic molecules through chemically-enhanced pathways mediated by ultraviolet radiation.

**In the solar system** Atmospheric discharges are observed in many forms in the solar system, with many aspects still poorly understood (e.g. Desch, 1992; Zarka et al., 2008; Aplin, 2013). On Earth, lightning is a common discharge phenomenon, augmented by volcanic eruptions (Cooray & Rachidi, 2017). There are also larger-scale 'transient luminous events' in the upper atmosphere, including giant red 'sprites', 'elves', and 'blue jets' (e.g. Boccippio et al., 1995). Details, also applied to transiting exoplanets, are given by Hodosán et al. (2016a).

At radio wavelengths, lightning-induced emission has been observed on Earth, probably on Venus (e.g. Russell et al., 2008), and on Jupiter (e.g. Gurnett et al., 1979; Rinnert et al., 1998), Saturn (Fischer et al., 2007b, 2011), Uranus (Zarka & Pedersen, 1986), and Neptune (Gurnett et al., 1990; Aplin, 2013).

In the optical, events have been detected (by Voyager, Cassini, and New Horizons) on Jupiter and Saturn (Smith et al., 1979; Little et al., 1999; Dyudina et al., 2004; Pérez-Invernón et al., 2017), although not from the ground (Luque et al., 2015).

**Exoplanets** For brown dwarfs and giant planets, the scale of discharges, energy deposited, and effects of cloud ionisation and coupling to large-scale magnetic fields, have been considered (Helling et al., 2011b,a, 2013; Rimmer & Helling, 2013; Stark et al., 2013b; Bailey et al., 2014a; Hodosán et al., 2016a).

Observationally, Zarka et al. (2012) estimate that lightning discharges 10<sup>5</sup> times more energetic than Jupiter could be detected on a gas giant at 10 pc. Bailey et al. (2014a) suggested that radio observations of brown dwarfs may contain hints of the presence of atmospheric lightning. Lightning-induced radio emission (§11.4.1), and the subsequent observability of HCN produced by lightning chemistry, has been considered as a contribution to the transit emission in the case of HAT-P-11 (Lecavelier des Etangs et al., 2013; Hodosán et al., 2016b). Hodosán et al. (2016a) extrapolated knowledge from Earth, including correlation with volcanic activity, compiled a list of 6 transiting planets (as well as the brown dwarf GJ 504 b) for which

**Detailed atmosphere models:** Many models of exoplanet atmospheres have been constructed, one of the main objectives being to interpret and predict transit and secondary eclipse fluxes. They cover • basic transit theory (Seager & Sasselov, 2000; Brown, 2001b; Heng et al., 2016), giant planet atmospheres (Burrows et al., 1997, 2001; Sudarsky et al., 2003; Seager et al., 2005a; Fortney, 2005; Burrows et al., 2006b), • inflated atmospheres (detailed in §6.28.4), • radiative-convective atmosphere theory (Hubeny et al., 2003; Guillot, 2010; Robinson & Catling, 2012; Vasquez et al., 2013a,b; Rauscher & Showman, 2014; Parmentier et al., 2015), • thermochemistry and elemental abundances (Lodders & Fogley, 1998; Burrows & Sharp, 1999; Lodders & Fogley, 2002; Lodders, 2003), • the chemistry of hot (super-)Earth atmospheres (Schaefer & Fogley, 2009; Schaefer et al., 2012), • disequilibrium chemistry (Cooper & Showman, 2006; Line et al., 2013b; Line & Yung, 2013; Line et al., 2014; Moses, 2014), • albedos (Marley et al., 1999; Sudarsky et al., 2000; Burrows et al., 2008b; Madhusudhan & Burrows, 2012; Heng & Demory, 2013), • giant planet models at wide separations (Burrows et al., 2004b; Burrows, 2005; Madhusudhan et al., 2011a), • orbital phase curves (Barman et al., 2005; Sudarsky et al., 2005; Fortney et al., 2006a; Showman et al., 2009; Burrows et al., 2010; Cowan & Agol, 2011a; Kane & Gelino, 2011b; Selsis et al., 2011; Cowan et al., 2013; Schwartz et al., 2016; Cowan et al., 2017; Haggard & Cowan, 2018), • irradiated atmospheres, inversions, heat transfer, circulations, zonal winds and day-side/night-side differences (Hubeny et al., 2003; Showman et al., 2006; Chabrier & Baraffe, 2007; Koskinen et al., 2007b,a; Langton & Laughlin, 2007; Cho et al., 2008; Dobbs-Dixon & Lin, 2008; Hansen, 2008; Showman et al., 2008a,b, 2009; Madhusudhan & Seager, 2010; Menou & Rauscher, 2010; Budaj et al., 2012; Liu & Showman, 2013; Medvedev et al., 2013; Perez-Becker & Showman, 2013; Showman & Kaspi, 2013; Amundsen et al., 2014; Parmentier & Guillot, 2014; Polichtchouk et al., 2014; Rauscher & Kempton, 2014; Cho et al., 2015; Showman et al., 2015; Dyudina et al., 2016; Komacek & Showman, 2016; Owen & Adams, 2016; Dobbs-Dixon & Cowan, 2017; Komacek et al., 2017; Zhang & Showman, 2017), including effects of obliquity (Rauscher, 2017), • supersonic shocks in irradiated atmospheres (Heng, 2012a; Christie et al., 2016; Fromang et al., 2016), • emission spectra of Earth-like planets (Kaltenegger et al., 2007), • transit spectra of Earth-like planets (Ehrenreich et al., 2006b; Kaltenegger & Traub, 2009), • theoretical exo-Neptune spectra (Spiegel et al., 2010a), • planet polarisation (Seager et al., 2000; Madhusudhan & Burrows, 2012), • formation and scattering due to clouds and hazes (Ackerman & Marley, 2001; de Kok et al., 2011a; Heng et al., 2012; Kitzmann et al., 2013; Marley et al., 2013; Morley et al., 2014; Wakeford & Sing, 2015; Feng et al., 2016b; Heng, 2016; Line & Parmentier, 2016; Parmentier et al., 2016; Sing et al., 2016; Bétrémieux & Swain, 2017; Gao et al., 2017; Heng & Kitzmann, 2017; Juncher et al., 2017; Ohno & Okuzumi, 2017), • effects of magnetic fields, magnetic drag and Ohmic dissipation (Castan & Menou, 2011; Menou, 2012b; Miller-Ricci Kempton & Rauscher, 2012; Rauscher & Menou, 2012b; Batygin & Stanley, 2014; Rogers & Komacek, 2014; Rogers, 2017; Cao & Stevenson, 2017), • the generation of atmospheric dynamos for the most highly irradiated (Rogers & McElwaine, 2017), • effects of refraction and multiple scattering (Robinson, 2017), and • the excitation of oscillations or pulsations via the suppression of radiative cooling (Dederick & Jackiewicz, 2017).

Many other studies have been made for specific systems, with goals of calculating planet/star flux ratios during secondary eclipse, characterising the atmospheric heat redistribution, atmospheric temperature and pressure profiles, and others. These are listed, in the bibliography of relevant transiting systems, in Appendix D.

follow-up may be most justified, and predicted large Saturnian-like events in the atmosphere of HD 189733 b during transit.

In protoplanetary disks, positrons released by the short-lived radionuclide <sup>26</sup>Al may lead to large-scale charging of dense pebble structures, resulting in neutralisation by lightning discharge and the flash-heating of dust and pebbles, perhaps responsible for the ubiquitous thermal processing seen in primitive meteoritic chondrules (Johansen & Okuzumi, 2018).

Electrostatic discharges have long been considered as a possible catalyst for the creation of prebiotic molecules respon-

sible for the origin of life (Miller, 1953), with recent detailed analyses of lightning shock-induced chemistry in exoplanet atmospheres under consideration (e.g. Rimmer & Helling, 2016; Ardaseva et al., 2017). Detectable emission could also reveal information on the local physical–chemical processes, and on the chemical composition of other atmospheres.

#### 11.4.2 General circulation models

As detailed in Section 11.4.1, close-in tidally locked hot Jupiters are subject to extreme stellar irradiation. This drives particularly strong asymmetric heating of their atmospheres, strong changes in chemical equilibrium conditions, the non-uniform formation of clouds and hazes, and the generation of high-velocity zonal winds which advect heat to the planet's night-side.

The fact that such powerful atmospheric circulation results in various observable consequences has, over the past decade, motivated the development of detailed 3d *general circulation models* (GCMs), often building upon existing Earth or other solar system atmospheric models, as a framework for the interpretation of exoplanet transmission and emission spectroscopy (§11.6). Similar models have also been used to describe the atmospheric circulation expected on Earth and super-Earth planets across a range of parameter space (§11.4.3), and to quantify the expected implications on habitability for tidally locked planets orbiting M dwarfs (§11.7.1).

General circulation models are based on the conservation laws of physics, variously expressed in finite-difference, spectral, or finite-element form (e.g. Seager, 2010; Heng et al., 2011b). Evolution of the circulation is computed by time integration of the primitive equations starting from some initial condition. Objectives include determining time-averaged zonal-mean temperatures and zonal winds, as a function of vertical height or pressure (e.g. Madhusudhan et al., 2014c). As in many highly complex systems, results are typically derived from large-scale numerical simulations, and are often somewhat non-intuitive.

In all these models, sources of forcing (e.g., stellar irradiation or internal heat generation) induce atmospheric motion, which are damped by sources of friction (e.g., viscosity or magnetic drag). An understanding of the atmospheric dynamics sets the background state (of velocity, temperature, density, and pressure) that determines the spectral and temporal appearance of an atmosphere. It also determines whether an atmosphere attains or is driven away from chemical, radiative, and thermodynamic equilibrium.

Some basic terminology is given in the accompanying box (page 592), while a chronology of some specific models and inferences applied to exoplanets is also given (box, page 593). Background insight may be gained from a top-level perspective of the highly complex and intensively studied Earth atmospheric circulation (box, page 594), while the solar system giants also

**GCM terminology:** GCM originally stood for (and does so here) General Circulation Model, the tools used for modeling climate. A second common usage, Global Climate Model, is not strictly synonymous and is more ambiguous: it may refer to an integrated framework that incorporates multiple components including a general circulation model, or to the general class of climate models.

In models of Earth's climate, Atmospheric GCMs (AGCM) model the *atmosphere*, contain prognostic equations that are a function of time (typically winds, temperature, moisture, and surface pressure), together with diagnostic equations that are evaluated from them for a specific time period. Ocean GCMs (OGCM) model the *ocean*, with fluxes from the atmosphere imposed, and may contain a sea ice model. AOGCMs combine the two, and remove the need to specify fluxes across the interface of the ocean surface. They are the basis for model predictions of Earth's future climate, such as those discussed by the IPCC.

In the context of these models, the concept of a *dynamical core* refers to codes that treat the essential atmospheric dynamics, and omit details such as radiative transfer. The *shallow water* approximation, a term used in terrestrial meteorology and oceanography, refers to models in which the horizontal extent greatly exceeds the vertical (or radial) dimension. A wider glossary of related terms is maintained at [glossary.ametsoc.org](http://glossary.ametsoc.org).

offer a perspective of the types of circulation that are also believed to occur on exoplanets (box, page 595).

**Framework** The simplest atmospheric circulation models for hot Jupiters (e.g. Showman & Guillot, 2002) divide the planet into two concentric spheres (Figure 11.22). The outer radiative part includes the low-mass atmosphere, extending down to pressures of 10–80 MPa, dominated by stellar heating (the planet's intrinsic luminosity being some factor  $10^4$  smaller than the energy absorbed from the star), and with possible horizontal temperature inhomogeneities. The deeper interior includes the convective core (and most of the mass) for which such inhomogeneities are smaller.

The existence of atmospheric winds, driven by the asymmetric heating, implies that the atmosphere is not synchronously rotating with the convective core. Details of the resulting zonal flows depend on the relative importance of the gravitational torques acting on the planet's (interior) tidal bulge, the gravitational torques on the atmosphere arising from spatial density variations associated with the surface meteorology, and the fluid-dynamical torques that transport (prograde or retrograde) angular momentum from the atmosphere to the interior. Typically, the gravitational tidal bulge is only slightly out of phase with the line-of-sight to the star (e.g.,  $\Delta\theta \sim 10^{-5}$  rad for Jupiter), while the angle between the meteorologically-induced density variations and the line-of-sight to the star may be up to 1 rad.

In the description of fluid flow in a rotating atmosphere, the ratio of advective to Coriolis accelerations in the horizontal momentum equation is characterised by

**GCM background and chronology:** Various 3d ‘general circulation models’ (§11.4.2) have been applied to the available data on exoplanet atmospheres. Many have been derived from existing terrestrial models. The following chronology, based on the review by Zalucha et al. (2013), provides a framework for understanding their development, differences, and applications.

*Hot Jupiters:* Showman & Guillot (2002) developed the first 3d GCM, for HD 209458 b, using the EPIC planet atmosphere model (Hsu & Arakawa, 1990; Dowling et al., 1998). It differed from previous brown dwarf models by the introduction of intense stellar irradiation, and from previous exoplanet models by the effects of advection. They predicted superrotating winds, with phase curve offsets. Cooper & Showman (2005) modeled HD 209458 b using the ARIES/GEOS dynamical core (Suarez & Takacs, 1995), with a more realistic radiative-equilibrium temperature, better resolution, and deeper circulation. Cooper & Showman (2006) used the same model to study the chemistry of HD 209458 b, with CO and CH<sub>4</sub> represented as passive tracers.

Cho et al. (2003) developed a GCM for HD 209458 b using the ‘equivalent barotropic formulation’, predicting a banded structure with three broad zonal jets and easterly equatorial flow. Menou et al. (2003) generalised this to other giant planets by varying the Rossby and Burger numbers, finding fewer zonal jets than the solar system giants. Cho et al. (2008) used a larger parameter space (including initial rms velocity and thermal forcing amplitude), and concluded that hot Jupiters have a polar vortex that revolves around each pole, with a small (2–3) number of zonal jets. Langton & Laughlin (2007) used a ‘shallow water’ model, finding a cold spot centred 76° east of the anti-stellar point, attributed to a difference in radiative time constant.

Showman et al. (2008a) modeled HD 209458 b and HD 189733 b using the MIT GCM dynamical core. Showman et al. (2009) used a scheme that calculated radiative transfer fluxes directly. Both showed flow from the substellar to anti-stellar point along the equator and over the poles at lower pressures, while a westerly equatorial jet and easterly polar flow developed at higher pressures. Menou & Rauscher (2009) used the Intermediate GCM dynamical core of Hoskins & Simmons (1975). Perna et al. (2010a) used the Rauscher & Menou (2010) GCM to show that magnetic drag could limit wind speeds.

Burkert et al. (2005) and Dobbs-Dixon & Lin (2008) showed that atmospheres with large opacity have a large day-night temperature difference, and *vice versa*. Dobbs-Dixon et al. (2010) found that high viscosity resulted in subsonic flow, while low viscosity produced supersonic flow. Langton & Laughlin (2008a) investigated the effect of high orbital eccentricities, finding that the atmospheric response was driven primarily by the irradiation at pericentre, and that the resulting expansion of heated air produced high velocity turbulent flow, with some planets also developing superrotating acoustic fronts. Thrastarson & Cho (2010) found that different initial states of the zonal jet lead to different results for circulation and temperature.

Heng et al. (2011b) performed ‘benchmark’ comparisons of both the spectral and finite difference dynamical cores of the GFDL Princeton FMS, applied to Earth, a tidally-locked Earth, a shallow hot Jupiter, and a deep circulation HD 209458 b, to determine whether differences are due to numerical procedures or ‘higher level’ physical effects, finding generally good agreement between the two in all but the deep HD 209458 b case. Similar benchmark tests have been reported for PUMA (Fraedrich et al., 2005; Bending et al., 2013). Perna et al. (2012) also used the Heng et al. (2011b) and improved FMS Heng et al. (2011a) models to show that irradiation is the main driver in radiative and dynamical properties, but that atmospheric opacity also plays a role. Oreshenko et al. (2016) included scattering, and applied it to the phase curves of Kepler-7 b.

*Hot Neptunes and super-Earths:* models for lower-mass close-in planets also typically assume that the planet is tidally locked. Lewis et al. (2010) used the Showman et al. (2009) GCM to study GJ 436 b, and found that with increasing metallicity, the circulation changed from one dominated by mid-latitude jets and minimal longitudinal temperature differences, to one dominated by an equatorial jet and large day–night temperature differences. Menou (2012a) used the Rauscher & Menou (2012a) GCM to model the super-Earth GJ 1214 b with various metallicities, and found robust superrotating equatorial jets.

Joshi et al. (1997) simulated a tidally-locked shallow atmosphere covering a thick rocky surface using a terrestrial planet GCM (James & Gray, 1986; Joshi et al., 1995), using a two-stream, grey radiative transfer representing a CO<sub>2</sub> or H<sub>2</sub>O gas. Heat was transported from day-side to night-side, with mass returned through the polar regions, and a superrotating equatorial jet.

Joshi (2003) used the Intermediate GCM (de Forster et al., 2000), adding non-grey radiative transfer, clouds, continents and oceans, along with evaporation, precipitation, and H<sub>2</sub>O-transport. The presence of a dry continent caused higher temperatures on the day-side, and allowed accumulation of snow on the night-side, while the absence of an ocean led to higher day–night temperature differences. Merlis & Schneider (2010) used the O’Gorman & Schneider (2008) GCM containing an active hydrologic cycle. They found that waves and eddies shaped the winds, temperature, and precipitation in rapidly rotating atmospheres, while simple divergent circulations dominated slowly-rotating atmospheres.

Heng & Vogt (2011) simulated the super-Earth GJ 581 g, varying the planet’s mass and density, the radiative cooling time, the mean surface pressure, and presence or lack of a troposphere. Selsis et al. (2011) used a version of LMD specifically developed for exoplanets (Selsis et al., 2011), to simulate a tidally-locked, synchronously-orbiting super-Earth with a CO<sub>2</sub> atmosphere. LMD (named for the Laboratoire de Météorologie Dynamique, Paris), was originally developed for the Earth (Sadourny, 1975; Hourdin et al., 2006), and uses the LMDZ 3d ‘dynamical core’ (Hourdin et al., 2006, 2013). It has been adapted to several terrestrial planet atmospheres in the solar system, notably Mars (Forget et al., 1999), Venus (Lebonnois et al., 2010), as well as Titan (Hourdin et al., 1995), and Triton 2010DPS....42.0606V.

Pierrehumbert (2011a) modeled GJ 581 g with the FOAM GCM (developed to study snowball Earth and other paleoclimate problems). They found that their ‘eyeball Earth’ simulations (i.e., mostly frozen planets with a pool of liquid H<sub>2</sub>O centred at the substellar point) could maintain liquid H<sub>2</sub>O at the surface. Wordsworth et al. (2011) simulated the super-Earth, GJ 581 d, using the LMD Mars model (Wordsworth et al., 2011) to determine stability conditions for a CO<sub>2</sub> atmosphere and liquid H<sub>2</sub>O.

Subsequent developments include the GPU-based THOR, which solves the 3d non-hydrostatic Euler equations, and relaxes the assumptions of shallow atmosphere and hydrostatic equilibrium (Mendonça et al., 2016); UM, the UK Meteorological Office ‘United Model’, which solves the full 3d Navier–Stokes equations with a height-varying gravity (Amundsen et al., 2016); and ROCKE-3D, a NASA–Goddard Institute 3d GCM, derived from their modern-Earth and near-term paleo-Earth Mode1E2, for a wide range of rocky planets (Way et al., 2017).

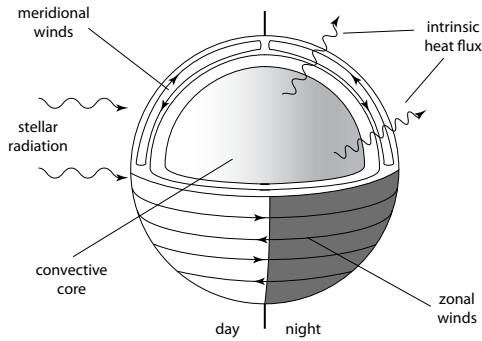


Figure 11.22: Dynamical structure of hot Jupiter planets: at  $P > 10 - 80$  MPa, the intrinsic heat flux is transported by convection. The convective core is at or near synchronous rotation with the star, and has small latitudinal and longitudinal temperature variations. At lower pressures a radiative envelope is present. The top part of the atmosphere is penetrated by stellar radiation on the day-side. The spatial variation in insolation drives winds that transport heat from the day-side to the night-side. After Showman & Guillot (2002, Figure 2).

the dimensionless Rossby number

$$Ro = u / (f_{\Omega} L), \quad (11.26)$$

where  $u$  is the mean horizontal wind speed,  $f_{\Omega} = 2\Omega \sin \phi$  is the ‘Coriolis parameter’ ( $\Omega$  is the angular rotation velocity, and  $\phi$  is latitude), and  $L$  is a characteristic length scale. Rossby numbers  $Ro = 0.03 - 0.3$  are expected for winds of planetary-scale and speeds from  $100 - 1000 \text{ ms}^{-1}$ . Non-linear advective terms are typically small compared to the Coriolis accelerations, which must then balance the pressure-gradient accelerations (box, page 594).

The zonal dependence, or ‘zonality’, compared with the zonal mean flow, is characterised by the Rhines’ wavenumber,  $k_{\beta} \sim (\beta/u)^{1/2}$ , where  $\beta$  is the derivative of  $f_{\Omega}$  with poleward distance. The associated half-wavelength, the Rhines’ scale  $L_{\beta}$ , provides an estimate of the jet widths for all four solar system giants (Liu & Schneider, 2010). For HD 209458 b,  $L_{\beta} \sim 1.5 \times 10^8 (u/1000 \text{ ms}^{-1})^{1/2} \text{ m}$ . For  $u \geq 400 \text{ m s}^{-1}$ ,  $L_{\beta} \geq R_p$ .

An upper limit to the wind speed,  $u_{\max}$ , can be derived from shear-instability considerations, and at  $P \sim 10^5 \text{ Pa}$  is of order  $3000 \text{ m s}^{-1}$ , compared with winds up to  $100 - 500 \text{ m s}^{-1}$  on the solar system giants. Estimates for HD 209458 b yield  $u_{\max} \sim 2400 \text{ m s}^{-1}$  at the tropopause. Characteristic time scales for zonal winds to redistribute temperature variations are then  $\tau_{\text{zonal}} \sim R_p / u_{\max}$ .

Superimposed on these large-scale zonal winds are vortices which arise in any non-idealised fluid flow, and can result in significant and long-lived features. Examples are seen in the weather patterns on Earth, in the atmospheres of the solar system gas giants (§10.3.5), and in detailed simulations of hot Jupiter atmospheres.

**Earth’s atmospheric circulation:** The major driver of Earth’s atmospheric circulation is non-uniform solar heating: largest near the equator and smallest at the poles. In broad terms, *Hadley cells* (named for George Hadley, amateur meteorologist, 1685–1768), on either side of the equator and encircling the Earth, are the source of warm air rising near the equator, which then flow poleward at 10–15 km altitude, descend in the subtropics, and return towards the equator near the surface.

This global energy transport, in which angular momentum transport and Coriolis forces also play a role, drives the prevailing winds and reduces the equator-to-pole temperature gradient.

In a little more detail (Schneider, 2006; Holton, 2012; Hartmann, 2016), warm moist air near the equator causes heavy precipitation which releases latent heat and drives strong rising motions (and drives the tropical rain-belts, hurricanes, and subtropical deserts). At the tropopause, it is forced poleward by the rising air below. It then cools, and gains an eastward component due to Coriolis acceleration, forming the subtropical jet streams. At about  $\pm 30^\circ$  latitude, the jet streams drive baroclinic instabilities that prevent the Hadley circulation from extending further poleward, and the now cool dry air begins to sink, warming adiabatically and decreasing in humidity. Near the surface, a frictional return flow absorbs moisture, and the Coriolis force gives it a westward component, creating the trade winds.

Of the various quantities used to characterise atmospheric circulation (e.g. Seager 2010, Chapter 10; Heng 2017) the *Rossby number*,  $Ro$  (which appears in the Navier-Stokes equation of viscous fluid flow) quantifies the importance of Coriolis acceleration due to rotation (Equation 11.26). Small  $Ro$  signifies a system strongly affected by Coriolis forces (resulting in *geostrophic balance* between Coriolis and pressure forces, and a *geostrophic wind* parallel to isobars, as in low-pressure weather systems), while large  $Ro$  signifies that inertial and centrifugal forces dominate (resulting in *cyclostrophic balance* between pressure gradient and centrifugal forces, as in tornados). In the oceans, all three forces are comparable, and  $Ro \sim 1$ . When  $Ro$  is large (either because  $f_{\Omega}$  is small, as at lower latitudes, or because the length scale  $L$  is small, or for large wind speeds  $u$ ), rotation can be neglected.

Further characterisation of atmospheric/oceanic flow is provided by the dimensionless *Burger number*,  $Bu$ , the ratio of density stratification in the vertical dimension, and planet rotation in the horizontal.  $Bu \sim 1$  implies nearly equal roles in governing vertical and other fluid motions. The dimensionless *Prandtl number* relates heat advection, heat diffusion, and viscous and inertial forces,  $Pr = C_p \mu / k$ , where  $C_p$  is the specific heat at constant pressure,  $\mu$  the dynamic viscosity, and  $k$  the thermal conductivity.

**Angular momentum transfer to the interior** Several mechanisms also transfer angular momentum between atmosphere and interior, including Kelvin–Helmholtz shear instabilities acting to smooth interior–atmosphere differential rotation, non-local waves which may enhance differential rotation (as in the ‘quasi-biennial oscillation’ on Earth), atmospheric tides forced by solar heating, as observed on Venus (Gold & Soter, 1969) and of particular relevance on super-Earths (Auclair-Desrotour et al., 2017a,b), and vertical advection in which the angular momentum in updrafts and downdrafts may differ.

**Winds and atmospheric circulation** The extreme incident heat flux on the day-side of close-in hot Jupiters drives winds that transport energy, momentum, and chemical species both horizontally and vertically (as observed in the Venusian mesosphere by Goldstein et al., 1991). The sound speed in the upper layers of hot Jupiter atmospheres is typically  $3\text{--}4\text{ km s}^{-1}$ ; flows moving at a substantial fraction of this speed are possible, and will affect the gross features of the atmospheric structure.

For close-in planets which are tidally locked, the stellar flux is always incident on the same illuminated hemisphere. This highly asymmetric heating drives strong atmospheric circulation which in turn may transport significant energy from the planet's day- to night-sides (Showman & Guillot, 2002; Cho et al., 2003).

The factor  $f$  in Equation 6.158 describes the effectiveness of this circulation. If the incident energy is efficiently redistributed by *advection* (bulk motion) to give an isotropic re-emission and uniform  $T_{\text{eq}}$  over both hemispheres, then  $f = 1$ . If the day-side alone reradiates the incident energy (and the night-side remains cold), its higher resulting  $T_{\text{eq}}$  is given by  $f = 2$ . Further adjustments to  $f$  can account for the angle of incidence of the stellar flux decreasing from the substellar point to the terminator, both in theoretical models (Burrows et al., 2003a), and in their interpretation (e.g. Harrington et al., 2006; Léger et al., 2009).

If the stellar radiation is absorbed high in the atmosphere, re-radiation is expected to dominate over radiation transport around the atmosphere due to bulk flow, resulting in a high temperature contrast between the illuminated and non-illuminated hemispheres. If, in contrast, the stellar radiation penetrates deep into the atmosphere before it is absorbed, advection can transport heat around the planet, resulting in a smaller temperature contrast (Showman et al., 2008b).

Reconstructing the longitudinally resolved brightness map of the day-side photospheric emission has been developed based on eclipse-mapping techniques (e.g. Williams et al., 2006; Rauscher et al., 2007b; Knutson et al., 2007a; Cowan & Agol, 2008).

Systems are known in which energy from the irradiated day-side is inferred to be efficiently redistributed throughout the atmosphere (e.g. HD 189733, Knutson et al., 2007a), and those in which there is almost no redistribution of energy from the day-side to the night-side (e.g. WASP-18 b, Nymeyer et al., 2011).

Models across a range of conditions (Heng & Workman, 2014; Heng et al., 2014) suggest that global atmospheric structure is largely controlled by a single parameter involving the Rossby and Prandtl numbers (§11.6).

Planets on long period highly eccentric orbits offer a particularly interesting configuration for atmospheric studies because of the periodic changes in irradiation that occur through pericentre (§11.6.3).

**Atmospheric circulation in the solar system giants:** Theories of Jupiter's atmospheric dynamics must explain a number of prominent features: the narrow stable bands and jets symmetrically disposed relative to its equator, the strong prograde (superrotating) equatorial jet, the origin and persistence of large vortices such as the Great Red Spot (§10.3.5), and other details such as lightning discharges (§11.4.1) and hot spots (Showman & Dowling, 2000). The Juno mission, ongoing as of 2018, is providing major new insights into its detailed radial structure (§12.2.2).

Early general circulation models for Jupiter were broadly divided into two classes: 'shallow' and 'deep' (box, page 592), and modern theories contain elements of both (e.g. Heimpel et al., 2005). The former treats the circulation as largely confined to a thin outer layer, which overlays some stable interior. The latter models the observed atmospheric flows as a surface manifestation of deeply rooted circulation in the outer molecular envelope (Busse, 1976). Shallow theories can explain the various narrow jets, but do not explain the strong prograde (superrotating) equatorial jet, which is naturally explained by deep models. The broad features are a consequence of the Taylor–Proudman theorem in fluid mechanics: in a fast-rotating barotropic ideal fluid (i.e., with density a function only of pressure), the flows occur in independent concentric cylinders parallel to the rotation axis. The planet's molecular H envelope then takes the form of a series of zones and belts, while the latitudes where the cylinders' outer and inner boundaries intersect with the visible surface correspond to the jets.

Atmospheric circulation in the other solar system giant planet varies widely: all exhibit alternating prograde and retrograde jets of different speeds and widths, with an equatorial jet that is prograde on Saturn as on Jupiter, and retrograde on Uranus and Neptune (e.g. Liu & Schneider, 2010). Flows are driven by a combination of differential radiative heating of the upper atmosphere, and by intrinsic heat fluxes originating from the deep interior (§6.28.4). Whether the equatorial jet is prograde or retrograde depends on whether the intrinsic heat flux is strong enough for convection to penetrate the upper atmosphere, exciting strong equatorial Rossby waves. The different speeds and widths of the non-equatorial jets (Figure 11.23) depend, among other factors, on the differential radiative heating of the atmosphere, the altitude of the jets, and the scale of macroturbulence set by the planet radius and rotation rate.

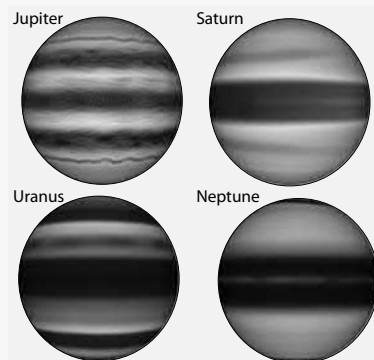


Figure 11.23: Illustrative zonal flows of the solar system giants, with grey scale encoding wind speed, from the simulations by Liu & Schneider (2010, Figure 3).

**Superrotation** The state of *superrotation* refers to an atmospheric circulation with persistent zonal-mean prograde (westerly) winds over the equator (wind direction being designated by the direction from which it flows; see §1.4). Earth, in contrast, is distinguished by equatorial easterlies (box, page 594). More precisely, superrotation refers to zonal mean winds with angular momentum  $M$  greater than the angular momentum of the surface at the equator,  $M_0 = \Omega R_p^2$ . If  $U$  is the mean zonal wind in a frame rotating with the angular velocity of the surface then, at latitude  $\theta$ ,  $M = R_p \cos\theta(\Omega R_p \cos\theta + U)$ , and  $M > M_0$  requires  $U > U_m$ , where  $U_m \equiv \Omega \sin^2\theta / \cos\theta$  (Held, 1999). Sustained equatorial superrotation requires the presence of torques generated by countergradient eddy angular momentum fluxes (Hide, 1969; Held & Hou, 1980). Non-equatorial superrotation would require particularly strong forcing (Held, 1999).

The infrared phase curves of various hot Jupiters, starting with HD 189733 b (Knutson et al., 2007a, 2009c, 2012), HD 209458 b (Zellem et al., 2014b), and WASP-43 b (Stevenson et al., 2014d), were found to show an eastward shifted ‘hot spot’, i.e. displaced downwind of the substellar point (§11.6.2), consistent with prograde (westerly) wind states in which the equatorial atmosphere spins faster than the planet surface. The effect has since been seen in other hot Jupiters, including Kepler-76 and HAT-P-7, and in the hot super-Earth 55 Cnc e (Demory et al., 2016a).

Other hot Jupiters show a *westward* phase shift between the brightest region on the planet surface and the substellar point, detailed further in Section 11.6.3.

**Detailed models** Superrotation was predicted for hot Jupiters by Showman & Guillot (2002). They describe the *eastward* hot spot offset as resulting from advection of the thermal field by a fast westerly equatorial jet stream, itself resulting from interactions with the mean flow of standing, planetary-scale waves induced by the day–night heating contrast (Showman & Polvani, 2011). If the radiative time constant is comparable to the characteristic time scale for air parcels to advect eastward over a planetary radius, then a significant eastward offset of the hot spot from the substellar point results.

General circulation models (box, page 593) have found superrotation to be a recurring feature of hot-Jupiter atmospheres, at least over certain ranges of incident flux and radiative time constants (e.g. Cooper & Showman, 2005; Showman et al., 2008a; Menou & Rauscher, 2009; Showman et al., 2009; Dobbs-Dixon et al., 2010; Li & Goodman, 2010; Perna et al., 2010a; Rauscher & Menou, 2010; Thrastarson & Cho, 2010; Heng et al., 2011b,a; Showman & Polvani, 2011; Dobbs-Dixon et al., 2012; Miller-Ricci Kempton & Rauscher, 2012; Perna et al., 2012; Rauscher & Menou, 2012a; Showman et al., 2013a; Mitchell et al., 2014; Peralta et al., 2014a,b; Tsai et al., 2014; Kataria et al., 2016; Penn & Vallis, 2017).

**Doppler measurements** High-resolution transmission spectra over a complete transit probe the average Doppler shift of atmospheric absorption around the planetary limb. In HD 209458 b, Snellen et al. (2010a) also used CRILES to reveal

a blueshift of  $2 \pm 1 \text{ km s}^{-1}$  in the average line profile of CO absorption. In HD 189733 b, Wyttenbach et al. (2015) used HARPS to show a blueshift (indicating net wind flows from the day-side to the night-side) of  $8 \pm 2 \text{ km s}^{-1}$  in the Na doublet.

Beyond the *average* Doppler shift, more robust tests of atmospheric circulation aim to probe the very different velocities predicted at the opposing limbs. Specifically, tidally-locked rotation combined with an eastward equatorial jet should result in absorption which is redshifted at the leading limb of the planet and blueshifted at the trailing limb (e.g. Miller-Ricci Kempton & Rauscher, 2012; Showman et al., 2013a).

Louden & Wheatley (2015) measured wind velocities on opposite limbs of HD 189733 b from Na absorption in HARPS transmission spectra. They found a strong eastward motion of the atmosphere, with a redshift of  $2.3_{-1.5}^{+1.3} \text{ km s}^{-1}$  on the leading limb and a blueshift of  $5.3_{-1.4}^{+1.0} \text{ km s}^{-1}$  on the trailing limb, consistent with a combination of tidally-locked planetary rotation and an eastward equatorial jet, and perhaps marking the first spatially resolved observation of an exoplanet. An alternative explanation in terms of excess chromospheric absorption in the emission cores was given by Barnes et al. (2016).

**Superrotation in the solar system** The solar system contains a number of instances of atmospheric superrotation, with Jupiter and Saturn being renowned examples (box, page 595). For these gas giants, the reference ‘surface’ rotation is taken as the deep interior rate inferred from the magnetic field.

The Venusian atmosphere exhibits several peculiarities revealed by spacecrafts and probes in the 1970–80s, including superrotating zonal winds peaking at  $100 \text{ m s}^{-1}$  near the cloud tops. This results in a 4-d rotation of the atmosphere, greatly exceeding the planet rotation of 243 d. General circulation models invoke thermal cells ascending around the equator and descending in polar regions, combined with the diurnal solar motion, which affects the angular momentum through tilted eddies and thermal tides (Lebonnois et al., 2010; Izakov, 2016; Cirilo-Lombardo et al., 2017). Superrotation also occurs in Titan’s atmosphere (e.g. del Genio et al., 1993; Lebonnois, 2012).

Earth’s stratosphere also superrotates in the westerly phase of the *quasi-biennial oscillation*, itself attributed to the countergradient vertical angular momentum transport by (boundary driven) Kelvin waves and eastward propagating gravity waves (Baldwin et al., 2001b). Superrotation on Earth may have existed in the past, as invoked to explain the Pliocene ‘permanent El Niño’ inferred from proxy observations (Tziperman & Farrell, 2009), and may be excited in a future global warming scenario (Pierrehumbert, 2000).

Along similar lines, numerical models have shown that electromagnetic torques lead to Earth’s solid inner core (box, page 663) rotating faster than the mantle (Glatzmaier & Roberts, 1996). Seismic evidence supports this inner core superrotation (e.g. Tromp, 2001; Dumberry & Mound, 2010).

### 11.4.3 Atmospheres of terrestrial planets

In contrast with the origin of the vast gaseous envelopes of the solar system gas giants via nebula accretion, three sources have been identified as the possible origin of the atmospheres of the terrestrial planets: the capture of nebular volatiles, outgassing during accretion, and outgassing from later tectonic activity. The specific case of the Earth’s atmosphere is considered in §12.3.8.



**Capture of nebular gas** In the core accretion model of gas giant formation, the capture of nebular gases is a fundamental process underlying the later stages of their growth. While nebula gas accretion has been considered as, at least, a partial contribution to the atmospheres of the terrestrial planets (e.g. Hayashi et al., 1979; Pollack & Black, 1982; Cameron, 1983; Ikoma & Genda, 2006; Stökl et al., 2015, 2016), its overall significance remains uncertain (Elkins-Tanton & Seager, 2008b; Zahnle et al., 2010). The argument underlying this view is that low-mass terrestrial planets are unable to capture and retain nebula gases during their early accretion phase, while nebular gases may have largely dissipated from the inner solar system by the time of final stages of planetary accretion.

Spanning the low-mass planets from Mars to the most extreme super-Earths,  $0.1M_{\oplus}$  to  $10 - 20M_{\oplus}$ , Lee & Chiang (2015) derived analytic expressions for how the atmospheric mass grows with time as a function of the underlying core mass  $M_{\text{core}}$  and nebular conditions, including the gas metallicity  $Z$ . Planets accrete as much gas as can cool: an atmosphere's doubling time is given by its Kelvin–Helmholtz time. Dusty atmospheres behave differently from atmospheres made dust-free by grain growth and sedimentation. They found that the gas-to-core mass ratio of a dusty atmosphere, across all orbital distances and nebular conditions, scales as

$$M_{\text{gas}}/M_{\text{core}} \propto t^{0.4} M_{\text{core}}^{1.7} Z^{-0.4} \mu_{\text{rcb}}^{3.4}, \quad (11.27)$$

where  $\mu_{\text{rcb}} \propto 1/(1 - Z)$ , for  $Z$  not close to 1, is the mean molecular weight at the innermost radiative–convective boundary. They give similar but more complex dependencies for dust-free atmospheres. They also show that, for the more massive super-Earths, heating from planetesimal accretion cannot prevent the planet from undergoing runaway gas accretion.

**Outgassing and volatiles by accretion** The terrestrial planets are believed to have formed within the solar nebula's snow line, where  $\text{H}_2\text{O}$  was not condensed. Theories of the origin of water on Earth (§12.1.4) consider instead that  $\text{H}_2\text{O}$  was acquired through impacts of comets and carbonaceous asteroids (e.g. Abe & Matsui, 1985; Matsui & Abe, 1986; Chyba, 1990), along with other surface volatiles such as  $\text{CH}_4$  (Butterworth et al., 2004; Court & Sephton, 2009; Sephton & Court, 2010; Ciesla et al., 2015). In the primitive class of chondritic meteorites (box, page 683) 'water' is mostly in the form of OH within silicate minerals – it is referred to as water since it most probably existed as  $\text{H}_2\text{O}$  when the mineral was formed, and is released as  $\text{H}_2\text{O}$  if the mineral melts.

On a given body, the efficiency of impact accretion and  $\text{H}_2\text{O}$  outgassing depends on the competition between impact delivery of new volatiles, and the impact erosion of those already present. For the inner solar system planets, Chyba (1990) argued that the net accumulation of planetary oceans was strongly favoured.

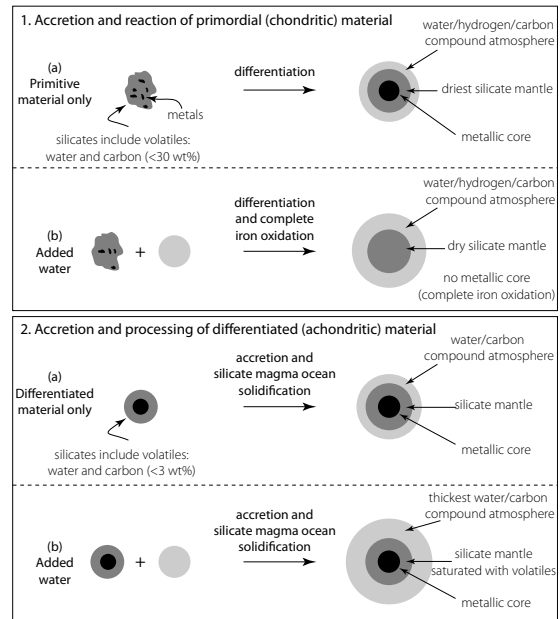


Figure 11.24: Schematic of the outgassing models of Elkins-Tanton & Seager (2008b). (1a) metallic Fe reacts with  $\text{H}_2\text{O}$  to form H and  $\text{FeO}_x$ , until the metallic Fe or  $\text{H}_2\text{O}$  is exhausted, resulting in an atmosphere of H and C compounds only. (1b)  $\text{H}_2\text{O}$  is added from an external source until all metallic Fe is oxidised, resulting a  $\text{H}_2\text{O}/\text{H}$  mixture, and C compounds. (2a) a molten achondritic silicate mantle solidifies, partitioning volatiles between silicates, liquids, and an atmosphere of  $\text{H}_2\text{O}$  and C compounds. (2b)  $\text{H}_2\text{O}$  is added, leading to solidification of the magma ocean, and an atmosphere of  $\text{H}_2\text{O}$  and C compounds. In all cases, traces of He and N are found in the atmosphere. Adapted from Elkins-Tanton & Seager (2008b, Figure 1), by permission of IOP Publishing/AAS.

**Detailed models** Elkins-Tanton & Seager (2008b) modeled outgassing during accretion to estimate the range of atmospheric mass and composition likely to exist on exoplanets ranging from  $1 - 30M_{\oplus}$ . They assumed that the material accreted is either primitive (chondritic), or differentiated (achondritic). In each case, additional  $\text{H}_2\text{O}$  and other volatiles is, or is not, accreted at the same time, giving four model configurations (Figure 11.24). This results in oxidising conditions during accretion, or reducing conditions during accretion, respectively. The latter can produce a planet with a metallic core and  $\text{H}_2\text{O}$ -rich atmosphere, while the former can produce planets without a metallic core but with a  $\text{H}_2$ -rich atmosphere.

Models of Elkins-Tanton & Seager (2008a) predict two planet types not present in the solar system: those consisting of silicate rock with no metallic core, and those with a deep  $\text{H}_2\text{O}$ -surface layer resulting directly from its initial solidification. Initial atmospheres range from below 1% to over 20% of the planet's total mass, with  $\text{H}_2\text{O}$  and C compounds dominating. H amounts to less than 6% of the planet mass, while He is found only in traces. Nitrogen, although in very low concentration in the accretion material, appears in sufficient quantity to build the  $\text{N}_2$ -based atmosphere of the Earth.

Schaefer & Fegley (2010) derived models aimed at an understanding of the early atmospheres of Earth and Mars, as well

as for interpreting spectroscopic observations of accreting exoplanets. They predicted dominant gases as a function of accreted chondritic material: H<sub>2</sub>O (for CI and CM chondrites), H<sub>2</sub> (ordinary H, L, LL as well as EH), CO (LH), and CO<sub>2</sub> (CV). They suggest that the atmospheres during the early accretion of Earth and Mars were probably H<sub>2</sub>-rich.

Rubie et al. (2015) studied the effects of impacts and accretion of embryos and planetesimals, in the context of the Grand Tack model (§12.6.4). They modeled the creation of a magma ocean, core formation, mixing and differentiation, and consequences for the composition of Earth's primitive mantle, the Martian mantle, the mass fractions of the metallic cores of Earth and Mars, and volatile delivery as a function of time.

**Outgassing through tectonics and volcanism** Later in the life of the planet, internal convection induced by heating (either primordial, radiogenic, or tidal) can augment the outgassing of volatiles locked in the mantle. Papuc & Davies (2008) estimated that, over a wide range of planet mass, volcanic outgassing may provide an atmosphere as massive as the Earth's in a few Gyr.<sup>3</sup>

Kite et al. (2008) estimated volcanism versus time for planets with Earth-like composition and masses up to 25M<sub>⊕</sub>, as a contribution toward predicting atmospheric mass on terrestrial exoplanets. They found that (1) volcanism is likely to proceed on massive planets with plate tectonics over the main-sequence lifetime of the host star; (2) plate tectonics may not operate on high-mass planets because of their buoyant crust which is difficult to subduct; and (3) melting is necessary but insufficient for efficient volcanic degassing; volatiles partition into the earliest, deepest melts, which may be denser than the residue and sink to the base of the mantle on young, massive planets. Magma must also crystallise at or near the surface, and the pressure of overlying volatiles must be fairly low, if volatiles are to reach the surface.

**Detailed models** Elkins-Tanton (2011) found that the greatest fraction of a terrestrial planet's initial volatile budget is degassed into the atmosphere at the end of magma ocean solidification (§11.3.7), leaving only a small fraction of original volatiles to be released into the atmosphere via later volcanism. Further H<sub>2</sub>O extrusion mediated by accretion impacts implies that H<sub>2</sub>O-oceans may be common on rocky super-Earths.

<sup>3</sup>There is a connection between theories of planetary formation, and more speculative theories of the origin of oil and 'natural gas' (primarily CH<sub>4</sub>) in Earth's crust. In the Russian-Ukrainian theory of deep abiogenic hydrocarbon formation (originating with Mendeleev 1877, and Kudryavtsev 1951), petroleum is considered not as a fossil fuel, but as a primordial material erupted at Earth's surface from depth. The *deep gas theory* (Gold, 1979, 1985, 1993; Gold & Soter, 1980), which differs in details rather than in principles, invokes deep faults as the pathway for the continuous migration of primordial CH<sub>4</sub> and other gases (including He) from Earth's upper mantle to the surface, where they are converted into higher hydrocarbons (oil and gas) in the upper crust. A review of both theories is given by Glasby (2006). While a biogenic origin is widely favoured, at least some abiogenic formation seems plausible (e.g. Scott et al., 2004; Proskurowski et al., 2008; Kolesnikov et al., 2009).

Various detailed studies have considered models for volcanic eruption, and prospects for spectroscopically detecting explosive volcanism (e.g. in SO<sub>2</sub>) during transit and secondary eclipse (Kaltenegger et al., 2010b); conditions for the existence of liquid H<sub>2</sub>O (Kadoya & Tajika, 2014); contributions from the tectonic outgassing of CH<sub>4</sub> (Levi et al., 2014); and the dependence on mantle viscosity, convective heat transport, and lithospheric thickness (Miyagoshi et al., 2014).

**Atmospheric models** Although observational constraints on the atmospheric properties of terrestrial exoplanets are not yet available, many theoretical and numerical studies have been carried out, especially in the context of habitability (§11.7). These models illustrate the great range of atmospheric conditions that will exist.

Atmospheric models for terrestrial planets and super-Earths aim to place constraints on the abundances of spectroscopically-observable gases, surface temperatures and pressures, albedos, and surface mineralogies, partly in anticipation of future observations (e.g. Miguel et al., 2011b; Schaefer & Fegley, 2011; Zsom et al., 2012; Hu et al., 2012b, 2013; Hu & Seager, 2014). Prospects for characterising terrestrial planet atmospheres have been considered, e.g., for JWST (Barstow et al., 2016), and for EChO (e.g. Leconte et al., 2015a).

Various reviews detail the application of general circulation models (§11.4.2) to terrestrial planets (Showman et al., 2013b; Forget & Leconte, 2014). For example, Showman et al. (2013b) covers the role of geostrophy, baroclinic instabilities, Hadley circulation, and the occurrence of jets; the key elements of the hydrological cycle, including the factors controlling precipitation, humidity, and cloudiness; and the key mechanisms by which the circulation affects the global-mean climate, and hence planetary habitability, in particular runaway greenhouse, transitions to snowball states, atmospheric collapse, and the links between atmospheric circulation and CO<sub>2</sub> weathering rates.

Kaspi & Showman (2015) used a moist atmospheric general circulation model, including a hydrological cycle, to demonstrate that equator-to-pole temperature differences, meridional heat transport rates, structure and strength of the winds, and the hydrological cycle, can all vary strongly with the planet properties, implying that the sensitivity of the planet to global climate feedbacks will depend significantly on the atmospheric circulation. They summarise the possible climatic regimes, and identify the mechanisms controlling the formation of atmospheric jet streams, analogues of the Hadley and Ferrel cells in Earth's atmosphere, and latitudinal temperature differences.

**Detailed models** Various other atmospheric models of Earths and super-Earths have been developed, as a function of stellar host (Godolt et al., 2015), detailing atmospheric species for a gas-melt equilibrium with a magma ocean (Ito et al., 2015), in a convecting condensable-rich atmosphere (Ding & Pierrehumbert, 2016), with an emphasis on gas accretion and retention

(Ginzburg et al., 2016b), in the presence of atmosphere–interior exchange in hot rocky planets (Kite et al., 2016), in the presence of clouds (Mbarek & Kempton, 2016), around rapidly rotating gravity-darkened stars (Ahlers, 2016), for chemical species connected to details of the protoplanetary disk (Cridland et al., 2016), a various general circulation models for tidally-locked planets (Carone et al., 2015; Gao et al., 2015; Haqq-Misra & Kopparapu, 2015; Carone et al., 2016; Koll & Abbot, 2016; Proedrou et al., 2016; Wordsworth, 2015), on the effects of de-gassing and re-gassing of H<sub>2</sub>O (Komacek & Abbot, 2016), of thermal inertias of icy planets (Ferrari & Lucas, 2016), and with a focus on estimating temperatures, water loss, and other atmospheric processes (Kasting et al., 2015; Tian, 2015b,a; Vladilo et al., 2015).

#### 11.4.4 Atmospheres of ejected planets

Although there is no observational evidence for the existence of true free-floating planets, present models suggest that rock and ice embryos, including those with  $M_p \sim 1M_\oplus$ , may be ejected from a young planetary system by gravitational scattering. Even in more mature architectures like the solar system, terrestrial-type planets may still be ejected (§12.4). Studies have addressed the atmospheric properties of such ejecta, and in particular whether they might support life as a result of sustained tidal heating of planet–satellite pairs.

**Isolated planets** Stevenson (1999) has reasoned that planets ejected into interstellar space may survive, with atmospheres, for billions of years.

An Earth-mass body develops an atmosphere with  $M_{\text{atm}}/M_p \sim 0.01$  assuming a pressure-induced opacity of hydrogen (Birnbaum et al., 1996), or  $M_{\text{atm}}/M_p \sim 0.001$  for more opaque models (Stevenson, 1982a). The atmospheric escape time after nebula clearing may be as short as 1 Myr at 1 au, but several Gyr in the interstellar medium if *sputtering*, viz. collisions with high-velocity interstellar atomic or molecular hydrogen, is also small.

An interstellar Earth-like planet 4.6 Gyr after formation would have a long-lived radionuclide-driven luminosity of  $4 \times 10^{13} (M_p/M_\oplus) W$  (Stacey & Davis, 2008). From consideration of the atmospheric pressure and opacity, Stevenson (1999) derived a surface temperature

$$T \sim 425 \left( \frac{M_p}{M_\oplus} \right)^{1/12} \left( \frac{M_{\text{atm}}/M_p}{0.001} \right)^{0.36} \text{ K}, \quad (11.28)$$

with  $T > 273 \text{ K}$  for basal pressures of  $10^8 \text{ Pa}$ , implying that bodies with liquid oceans are possible in interstellar space. They may have volcanic cores, and dynamo-driven magnetic fields with large magnetospheres.

**Planet–satellite pairs** Debes & Sigurdsson (2007) found that interactions between giant planets and terrestrial-sized protoplanets with lunar-sized satellites led to 3.3% cases in which only the Earth-mass planet is ejected, while 4.6% ended in the ejection of a bound Earth–Moon type system. In most cases the eccentricity of the bound pair increases, thereafter supplying heating of the planet through tidal circularisation, and augmenting that from interior radionuclides.

*Table 11.4: A comparison of various planet heat sources. Earth's internal heat comes from a combination of residual heat from planetary accretion (about 20%), the balance largely from radioactive decay (Turcotte & Schubert, 2002, p136). Currently  $^{40}\text{K}$ ,  $^{238}\text{U}$ ,  $^{235}\text{U}$ , and  $^{232}\text{Th}$  are the primary radiogenic heat sources in the Earth (Stacey & Davis, 2008); heat generation now is 2–3 times less than in the Archean era (3.8–2.0 Gyr). For the ejected systems, energies are typical tidal heat dissipations from the simulations of Debes & Sigurdsson (2007).*

Heat source	Energy (W)
Solar insolation (Earth, present day)	$1.5 \times 10^{17}$
Radiogenic heating (Earth, present day)	$4 \times 10^{13}$
Radiogenic heating (Earth, Archean era)	$1 \times 10^{14}$
Tidal heating on Io (Veeder et al., 1994)	$1 \times 10^{14}$
Ejected Earth–Moon (tidal, rocky)	$4.2 \times 10^{15}$
Ejected Earth–Moon (tidal, icy)	$2.1 \times 10^{16}$

Similar tidal heating has been investigated in relation to the thermal history of the Moon (Peale & Cassen, 1978), tidal heating and vulcanism on Io (§10.11.9), the heating of Europa (Cassen et al., 1979; Carr et al., 1998), and in assessing the long-term fate of the solar system (Laughlin & Adams, 2000).

Debes & Sigurdsson (2007) give the following expressions for tidal heating arising from circularisation of the satellite's eccentric orbit, and from synchronisation between the planet's spin and the satellite's mean motion, respectively

$$H_{\text{circ}} = -\frac{63e^2n}{4\bar{\mu}Q_p} \left( \frac{R_p}{a} \right)^5 \frac{GM_s^2}{a}, \quad (11.29)$$

$$H_{\text{sync}} = -(\omega - n) \frac{3k_{2p}}{Q_p} \frac{M_s^2}{M_s + M_p} \left( \frac{R_p}{a} \right)^5 n^2 a^2 (\omega - n), \quad (11.30)$$

where  $n$  is the mean motion,  $M_s$  is the satellite mass,  $M_p$  is the planet mass,  $\bar{\mu}$  is the ratio of elastic to gravitational forces (the effective rigidity of the planet),  $k_{2p}$  is the planet's Love number,  $\omega$  its orbital rotation, and  $Q_p$  its specific dissipation function. For a rocky planet they assume  $k_{2p} = 0.299$ ,  $\bar{\mu} = 4$ ,  $Q_p = 12$ . For an icy planet they assume  $k_{2p} = 0.7$ ,  $\bar{\mu} = 1$ ,  $Q_p = 100$ . A comparison of the various resulting heat sources is given in Table 11.4.

With various assumptions, they estimate a local space density of such ejected pairs as  $\sim 10^{-3} \text{ pc}^{-3}$ . Their detection would be difficult based on thermal radiation peaking at  $\sim 80 \mu\text{m}$ , or on their non-thermal radio emission, but more plausible via gravitational microlensing.

Tidal heat production declines with time. Debes & Sigurdsson (2007) estimate that it drops to radiogenic levels after 140 Myr for a rocky planet, and after 246 Myr for an icy planet, perhaps time enough 'for life to arise and adapt to the decreasing temperatures'.

#### 11.4.5 Atmospheric erosion

Various processes can erode an existing atmosphere, some more relevant in the early stages of planet formation, and some of particular relevance to gas giants or close-in highly irradiated planets.

**Planetesimal erosion** The same type of accreting impact responsible for the build-up of volatiles on the terrestrial planets can also erode an existing atmosphere. Of most importance is the effect of the late stages of

residual planetesimal impacts, which may result in significant or even catastrophic ablation, either through multiple small impacts, or one or more larger impacts. The efficiency of atmospheric ejection is related to the impactor mass and the atmospheric scale height (O’Keefe & Ahrens, 1982; Ahrens, 1993; Newman et al., 1999; Schlichting et al., 2015).

For hot Jupiters, planetesimal impacts during formation, being ablated rather than sinking to the core, can have a significant effect on the final atmospheric composition (Mordasini et al., 2016; Pinhas et al., 2016).

**Evidence from the solar system** Prescriptions for the early solar system impactor flux, based on observed cratering of Mars and the Moon, have been given by Tremaine & Dones (1993) and Melosh & Vickery (1989). The latter are based on the Schmidt–Holsapple scaling law for silicate projectiles (Schmidt & Housen, 1987), which equates the impact flux to a crater density assuming an average impact velocity of  $20 \text{ km s}^{-1}$ , mean impact angle of  $45^\circ$ , and a rim-to-rim diameter 25% larger than the apparent transient crater diameter (Figure 11.25).

In the form given by Kuchner (2003, eqn 5), and based on the solar system model, the number of projectiles per year of mass greater than  $m_p$  that fall on a planet of (effective gravitational) radius  $R_p$  is

$$N = 0.25 \text{ yr}^{-1} \left( \frac{R_p}{R_\oplus} \right)^2 \left( 1 + 2300 e^{-t/2.2 \times 10^8 \text{ yr}} \right) \times \left( \frac{m_p}{1 \text{ kg}} \right)^{-0.47}. \quad (11.31)$$

Considering impactors with masses between  $10^{15} \text{ kg}$  and  $0.01 M_{\text{Moon}}$  on a planet with  $R_p = R_\oplus$ , Kuchner (2003) derived a total impact mass of  $< 0.003 M_\oplus$ , allowing the survival of even a volatile-rich planet of  $0.1 M_\oplus$ .

This size distribution model breaks down for high-mass impactors (Tremaine & Dones, 1993). Such giant impacts probably created Earth’s Moon (§12.4), may have spun up Mars (Dones & Tremaine, 1993a), stripped Mercury’s silicate mantle (Benz et al., 1988), and largely removed (in the case of Mars) or diminished (in the case of Venus) the primordial atmospheres of some of the terrestrial planets (Cameron, 1983). Models for Mars include impact heating, formation of a shallow magma ocean, and enhanced outgassing and escape to space for some 0.6 Myr after formation (Maindl et al., 2015).

**Evidence from noble gases** Further evidence for collisional atmospheric erosion may come from the radiogenic and primordial noble gas content of the Venus, Earth and Mars atmospheres. These show a several order-of-magnitude decrease in  $^{20}\text{Ne}$  and  $^{36}\text{Ar}$  (but a nearly constant ratio) progressing from Venus to Mars. Thus, atmospheric abundances of  $^{36}\text{Ar}$  are, in relative mass (kg per kg of planet)  $2.5 \times 10^{-9}$  for Venus,  $3.5 \times 10^{-11}$  for Earth, and  $2.1 \times 10^{-13}$  for Mars.

These and other noble gas trends were originally attributed to grain accretion, and were assumed to reflect conditions in the solar nebula at the time of formation of the planetary atmospheres (Pollack & Black, 1979; Wetherill, 1980; McElroy & Prather, 1981; Pollack & Black, 1982). But Cameron (1983) argued that the Earth lost essentially all of its primordial Ar due to the collisional Moon-forming event, and that the amount now present represents that brought in by late accretion.

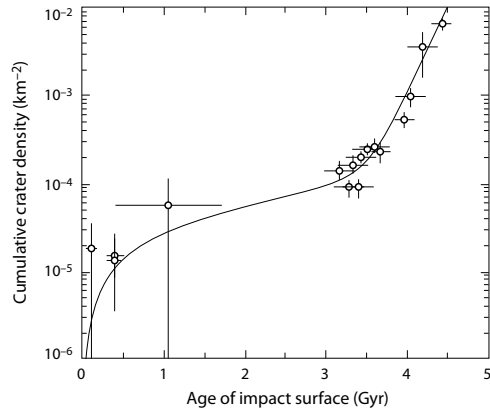


Figure 11.25: Comparison between the lunar impact crater density, and that predicted by the impactor model of Melosh & Vickery (1989). The model yields a cumulative density for craters exceeding 4 km diameter of  $N(> 4 \text{ km}) = 2.68 \times 10^5 [T + 4.57 \times 10^{-7} (e^{\lambda T} - 1)]$ , where  $T$  is the age of the cratered surface, and  $\lambda = 4.53 \text{ Gyr}^{-1}$ . Crater density data is from Kaula et al. (1981, Table 8.4.2). From Melosh & Vickery (1989, Figure 2), by permission from Nature/Springer/Macmillan Ltd, ©1989.

**Giant impacts** The very largest impacts, likely to be a frequent product of terrestrial planet formation (§10.6.4), will render the surviving planet hot and potentially detectable. For terrestrial planets enveloped by thick atmospheres consisting predominantly of  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , Lupu et al. (2014) modeled the post-impact atmospheric chemistry in equilibrium with hot surfaces with composition reflecting either the bulk silicate Earth or its continental crust. These atmospheres are dominated by  $\text{H}_2\text{O}$  and  $\text{CO}_2$ , while  $\text{CH}_4$  and  $\text{NH}_3$  are quenched. Other important constituents are  $\text{HF}$ ,  $\text{HCl}$ ,  $\text{NaCl}$ , and  $\text{SO}_2$ , likely to be apparent in the emerging spectra, and indicative that an impact (or increased volcanism, Kaltenecker & Sasselov, 2010) has occurred. The hottest post-giant-impact planets would be detectable with near-infrared ( $1\text{--}4 \mu\text{m}$ ) coronagraphs on 30-m telescopes. Cooling time scales of  $10^5\text{--}10^6 \text{ yr}$  suggests that tens of such planets could be discovered.

**Jeans escape** In *Jeans escape*, also called Jeans evaporation or thermal escape, individual molecules from the high-velocity tail of the thermal Maxwell–Boltzmann distribution may reach escape velocity and overcome the planet’s gravity field. The mechanism defines the uppermost layer of an atmosphere, the *exosphere*. Its lower boundary, the *exobase* or thermopause, is the height at which the molecular mean free path is equal to one pressure scale height, such that upward traveling particles are on a ballistic trajectory. The exosphere is the transition zone between the atmosphere and interplanetary space, with the altitude of the Earth’s exobase ranging from 250–500 km depending on solar activity.

The relevant parameter describing atmospheric loss is the dimensionless Jeans parameter, the ratio of gravitational to thermal energy (proportional to mass)

$$\lambda_J = \frac{v_{\text{esc}}^2}{v_p^2}, \quad (11.32)$$

where  $v_p$  is the most probable velocity of the distribution, and  $v_{\text{esc}}$  is the escape velocity at the exobase. Thermal escape becomes important for  $\lambda_J \lesssim 10$ .

**Solar system giants** For the high-gravity cold solar system gas giants, Jeans escape is insignificant, with  $\lambda_J$  at their exobases of 480, 420, 50, and 120 for Jupiter, Saturn, Uranus and Neptune (Strobel, 2002; Hunten, 2002). For planets of smaller mass and higher temperature, such as Earth, only light atoms escape (e.g. Irwin, 2006, Table 3.1).

**Hot Jupiters** Soon after discovery of the first hot Jupiter, 51 Peg, orbiting 100 times closer than Jupiter, Guillot et al. (1996) showed that the planet is stable to classical Jeans escape (and also to photodissociation and extreme ultraviolet-induced mass loss), even under extreme conditions of tidal locking. They estimated a mass loss rate of  $10^{-16} M_{\odot} \text{ yr}^{-1}$ , or  $10^{-4} M_J$  over 1 Gyr. Other simulations have since been applied to various other systems (e.g. Salz et al., 2016; Volkov, 2016, and references). Effects of X-ray irradiation on mass loss have subsequently been considered separately for G dwarfs (Penz et al., 2008), and M dwarfs (Penz & Micela, 2008).

With the discovery of even closer-in, low-density planets, Fossati et al. (2017a) generalised the Jeans escape parameter taking hydrodynamic and Roche lobe effects into account. With  $\Lambda$  defining the Jeans escape parameter for H at the observed planet radius and mass for the planet's equilibrium temperature they found that planets with  $\Lambda < 15 - 35$  lie in the 'boil-off' regime, where the escape is driven by the atmospheric thermal energy and low planetary gravity. The atmospheres of hot ( $T_{\text{eq}} \geq 1000 \text{ K}$ ) low-mass ( $M_p \leq 5 M_{\oplus}$ ) planets with  $\Lambda < 15 - 35$  shrink to smaller radii, and out of the boil-off regime in  $\lesssim 500 \text{ Myr}$ . Cubillos et al. (2017b) used this parameterisation to identify 27 out of 167 Neptune-like planets likely to exhibit extreme mass-loss rates.

**Hydrodynamic escape** In *hydrodynamic escape*, a thermally-driven Jeans escape of light atoms or molecules can carry heavier species along with it through collisional drag (e.g. Shizgal & Arkos, 1996). The mechanism requires a continuous energy source at altitude to maintain the high-velocity tail. For an atomic gas, the transition from hydrodynamic to Jeans escape occurs over  $\lambda_J \sim 2 - 3$  (Volkov et al., 2011).

Thermally sustained by planetesimal accretion during early formation, hydrodynamic escape has also been invoked to explain the anomalous noble gas isotope ratios of Venus, Earth, and Mars (Zahnle et al., 1990). The effect is compounded by EUV heating, conduction, and tidal forces (Watson et al., 1981).

Mass-loss due to the stellar extreme-ultraviolet flux  $F_{\text{EUV}}$  can be estimated by assuming that the flux received by the planet  $\pi F_{\text{EUV}} (R_{\star}/a)^2 R_p^2$  is converted into work against its gravitational field with efficiency  $\eta$  (e.g., Watson et al., 1981; Sanz-Forcada et al., 2011)

$$\dot{M} = \pi \eta F_{\text{EUV}} \left( \frac{R_{\star}}{a} \right)^2 \frac{R_p^3}{GM_p} = \pi \eta F_{\text{EUV}} \left( \frac{R_{\star}}{a} \right)^2 \frac{R_p}{g}, \quad (11.33)$$

where the planet surface gravity  $g_p = GM_p/R_p^2$ .

Kuchner (2003) evaluated survival time against volatile atmospheric escape as a function of planet mass

and orbital distance, finding that an Earth-mass volatile-rich planet even at 0.3 au from a Sun-like star can retain its volatiles for the age of the solar system. Nevertheless, the steady atmospheric erosion means that such ocean planets should be more common around young stars, and stars with lower time-averaged EUV luminosity. Compared to the FGK type main sequence stars, M stars would be particularly hospitable to close-in volatile Earth-mass planets.

An extreme case is KELT-9 b, in a 1.5-d orbit transiting the very hot (A0-type,  $T_{\text{eff}} \sim 10170 \text{ K}$ ) host star HD 195689 (Gaudi et al., 2017). With a day-side temperature of  $T_{\text{eq}} \sim 4600 \text{ K}$ , it receives 700 times more extreme-ultraviolet radiation than the next hottest, WASP-33 b ( $T_{\text{eq}} \sim 2710 \pm 50 \text{ K}$ , Collier Cameron et al., 2010b), implying a mass-loss rate that could leave it stripped of its envelope during the star's main-sequence lifetime.

Irradiation may be relevant even at large orbital separations. Over Pluto's lifetime, the solar EUV-driven wind may have led to the erosion of several km of Pluto's surface ice (Watson et al., 1981; Hunten & Watson, 1982; Trafton et al., 1997), and a small fraction of its total mass through  $\text{N}_2$  escape (Tian & Toon, 2005).

Related studies of the X-ray/extreme ultraviolet flux as a function of spectral type and stellar age are discussed further in Section 8.10.4.

**Detailed models** Many detailed models of X-ray/EUV heating, mass-loss rates, lifetimes, and particle trajectories have been made, both for hot Jupiters (e.g. Lammer et al., 2003; Lecavelier des Etangs et al., 2004; Yelle, 2004; Lecavelier des Etangs, 2007; Yelle et al., 2008; Murray-Clay et al., 2009; Odert et al., 2010; Ehrenreich & Désert, 2011; Guo, 2011; Sanz-Forcada et al., 2011; Iorio, 2012b; Erkaev et al., 2013; Guo, 2013; Johnson et al., 2013; Cherenkov et al., 2014; Gronoff et al., 2014; Koskinen et al., 2014a; Kurokawa & Nakamoto, 2014; Lanza, 2014; Shaikhislamov et al., 2014; Salz et al., 2015; Tripathi et al., 2015; Beth et al., 2016a,b; Chadney et al., 2016; Erkaev et al., 2016; Owen & Alvarez, 2016; Volkov, 2017), as well as for super-Earths, terrestrial planets, and satellites (e.g. Lammer et al., 2008; Tian, 2009; Lammer et al., 2011c, 2013b; Jin, 2014; Kurosaki et al., 2014; Owen & Wu, 2016; Dong et al., 2017a).

**Photolytic dissociation** The loss of volatiles by Jeans or hydrodynamic escape may be further accelerated by photolytic dissociation under ultraviolet irradiation (§11.4.1). For example,  $\text{NH}_3$  would be converted into  $\text{N}_2$  and  $\text{H}_2$  in less than 2 Gyr for a planet at 1 au from a G2V star (Léger et al., 2004). Dissociation of  $\text{H}_2\text{O}$  in a transiting terrestrial or ocean planet may be detectable through ultraviolet absorption in the Lyman lines of atomic hydrogen (Jura, 2004).

Vigorous stellar activity adds to the depletion, with coronal mass ejections in M stars possibly removing atmospheres in the habitable zone (Lammer et al., 2007; West et al., 2008). With its low surface gravity, impact erosion by the solar wind may have reduced the atmosphere of Mars from an initial pressure of  $10^5 \text{ Pa}$  to its current  $\text{CO}_2$ -dominated mean surface level pressure of

~600 Pa over the lifetime of the solar system (Melosh & Vickery, 1989). Without sufficient shielding by a magnetosphere, an Earth-like planet with  $a < 0.2$  au could lose its atmosphere in ~1 Gyr (Lammer et al., 2007).

**Stripping of hot Jupiters and Neptunes** For close orbiting systems in the range 0.01–0.1 au, significant hydrodynamic escape is predicted, although at rates that may still leave atmospheres stable for several Gyr (Guillot et al., 1996; Yelle, 2004; Tian et al., 2005). Observations of HD 209458 b, for example, indicate the escape of H I (Vidal-Madjar et al., 2003; Ehrenreich et al., 2008) as well as O I and C II (Vidal-Madjar et al., 2004), while still leaving the strongly irradiated planet stable against hydrodynamic escape.

Significant atmospheric evaporation will be compounded by inward migration and Roche lobe overflow (Trilling et al., 1998, 2002; Jaritz et al., 2005; Erkaev et al., 2007), with a resulting inflation of the outer atmospheric layers (Baraffe et al., 2004; Hubbard et al., 2007).

**Examples** Strong evaporation and/or tidal stripping may be responsible for the formation of hot-Neptunes such as GJ 436 b and 55 Cnc e, and it is possible that the more gaseous hot Jupiters and the higher-density hot Neptunes may share the same origin and evolution history (Baraffe et al., 2005, 2006).

CoRoT-7 b is an example of a giant planet that may have been largely stripped of its H/He envelope due to its host star proximity. The remaining rocky or metallic core would resemble a terrestrial planet. The hypothetical class of stripped giants has been termed a *chthonian planet* (Hébrard et al., 2004).

**Radius limits for rocky planets** For the Kepler planets with  $P \leq 100$  d, mass and radius constraints have shown that rocky planets, without thick proto-atmospheres, are only found up to  $1.5 - 2R_{\oplus}$  (e.g. Marcy et al., 2014; Weiss & Marcy, 2014; Dressing et al., 2015; Rogers, 2015; Buchhave et al., 2016; Demory et al., 2016a). This distinction between rocky and gas-enveloped planets has been attributed either to low-mass planets not forming thick atmospheres, or to their originally thick atmospheres being easily lost through X-ray and extreme ultraviolet erosion (Owen & Wu, 2016; Lehmer & Catling, 2017).

**Detailed models** Lehmer & Catling (2017) simulated hydrodynamic escape across a wide range of models, and showed that the large cross-section for extreme ultraviolet absorption in the distended primitive atmospheres of low-mass planets results in complete atmospheric loss during the 100 Myr phase of stellar extreme ultraviolet saturation (§8.10.4). In contrast, more massive planets have less distended atmospheres and less escape, and so retain thick atmospheres through the extreme ultraviolet saturation phase, and then indefinitely as the extreme ultraviolet fluxes drop over time. With a cutoff between rocky and gas-enveloped planets that agrees with the observed distribution, they concluded that hydrodynamic escape plausibly explains the observed upper limit on rocky planet size, and the few planets found in the  $1.5 - 2R_{\oplus}$  range.

## 11.5 Mass–radius relation

Exoplanets span a wide range of mass, composition, and atmospheric and internal structure, and wide ranges of properties such as age, temperature, rotation, irradiation, tidal distortion, and magnetic field. Combination of their masses (from various dynamical models) and radii (estimated from transit measurements) provide an estimate of their mean densities, while trends in the mass–radius relation convey insights into their composition, internal structure, and formation mechanism.

A review of the overall form and content of the mass–radius relationship extending from solar-type stars to terrestrial planets is given by Chabrier et al. (2009), and is illustrated over this entire range in Figure 6.100. The observed mass–radius relation for transiting planets is described further in Section 6.27.

As of the end of 2017, of more than 3500 known exoplanets, there are some 50 in the range  $1 - 10M_{\oplus}$ , whose radii (mostly from Kepler) and masses (from a range of follow-up methods) are known to better than 30%. For these, characteristics of the mass–radius relation are beginning to allow some detailed comparisons with theory.

### 11.5.1 General features

The forms of the mass–luminosity and mass–radius diagrams are broadly explained by current theories of planet formation, as replicated in population synthesis models (§10.13.3). For example, since low-mass planets cannot bind massive H–He envelopes, while supercritical cores necessarily trigger runaway gas accretion, ‘forbidden zones’ are found in the mass–radius plane (Figure 10.52). For a given mass, there is a considerable diversity of radii, mainly due to different bulk compositions, and reflecting different formation histories.

Analyses frequently consider a simply power-law relation between planet mass and radius

$$\frac{R_p}{R_{\oplus}} = k \left( \frac{M_p}{M_{\oplus}} \right)^{\beta}. \quad (11.34)$$

While no single value of  $\beta$  can apply to all masses and compositions, the parameterisation is useful when comparing theory and observations over restricted ranges. For terrestrial planets, for example, such a relation quantifies the extent to which a planet deviates from the  $R \propto M^{1/3}$  relation expected if the interiors were homogeneous and incompressible.

Over various mass intervals (e.g. Mordasini et al., 2012b, Section 7.9) a fit to the terrestrial planets of the solar system yields  $\beta = 0.33$ , as for constant density spheres (Wolfgang & Laughlin, 2012; Wolfgang et al., 2016), while a fit to Earth and Saturn gives  $\beta = 0.48$  (Lissauer et al., 2011b), with  $k = 1$  in both cases. Theoretical models suggest that  $\beta = 0.27$  for scaled versions of the Earth in the  $1 - 10M_{\oplus}$  regime (Valencia et al., 2006),

and  $\beta \sim -1/8$  for massive gaseous planets of about  $10M_J$  (Chabrier et al., 2009).

Above  $\sim 4M_J$ , planetary radii decrease with mass, a consequence of the combined effects of a change in interior composition and increasing degeneracy of the matter. The specific dependence of  $\beta$  on mass then provides a proxy for their bulk interior composition.

Planets with sizes between those of Earth and Neptune divide into two populations: purely rocky bodies whose atmospheres contribute negligibly to their sizes, and larger gas-enveloped planets possessing voluminous and optically thick atmospheres. Whether a planet forms as rocky or gas-enveloped depends on the solid surface density of its parent disk, and the envelope's contribution determines the details of the relevant mass–radius relation (Dawson et al., 2015a).

### 11.5.2 Terrestrial planets and super-Earths

From structural models of Earths and super-Earths (§11.3.5), various more detailed mass–radius relations have been derived according to assumed composition (e.g. Léger et al., 2004; Valencia et al., 2006; Fortney et al., 2007b; Seager et al., 2007; Sotin et al., 2007; Valencia et al., 2007b; Adams et al., 2008; Zeng & Seager, 2008; Grasset et al., 2009; Rogers et al., 2011; Wagner et al., 2011; Mordasini et al., 2012b; Swift et al., 2012; Batygin & Stevenson, 2013; Militzer & Hubbard, 2013; Zeng & Sasselov, 2013; Howe et al., 2014; Lopez & Fortney, 2014; Weiss & Marcy, 2014; Dorn et al., 2015; Thomas & Madhusudhan, 2016; Wolfgang et al., 2016; Zeng et al., 2016; Zeng & Jacobsen, 2016; Mills & Mazeh, 2017).

Expressed as the simple power-law (Equation 11.34), Sotin et al. (2007) found  $(k, \beta) = (1, 0.306)$  and  $(1, 0.274)$  for terrestrial planets of solar composition (and minimal H<sub>2</sub>O content) in the ranges  $0.01 - 1M_\oplus$  and  $1 - 10M_\oplus$  respectively. For 50% water content, corresponding to the class of ‘ocean planets’, they found  $(k, \beta) = (1.258, 0.302)$  and  $(1.262, 0.275)$  for the same mass ranges. The essentially identical exponent means that, independent of mass, a 50% H<sub>2</sub>O planet is predicted to be 25% larger than a terrestrial planet (and the surface gravity correspondingly smaller).

Valencia et al. (2007b) gave a more general power-law expression as a function of the H<sub>2</sub>O-ice mass fraction, under the further assumption that the mantle-to-core ratio remains constant (such that the Fe/Si ratio is itself approximately constant, and consistent with the solar nebula composition). They gave

$$R_p = (1 + 0.56i) R_\oplus \left( \frac{M_p}{M_\oplus} \right)^{0.262(1-0.138i)}, \quad (11.35)$$

where  $i$  denotes the ice mass fraction in percent.

With a particular scaling of mass and radius, Seager et al. (2007) derived an expression for  $M_p \lesssim 20M_\oplus$  more

related to their underlying approximation to the equation of state (Equation 11.15), viz.

$$\log R'_p = k_1 + (1/3) \log(M'_p) - k_2 M'_p{}^{k_3}, \quad (11.36)$$

where  $M'_p$  and  $R'_p$  are the scaled mass and radius, and  $k_1, k_2, k_3$  are obtained from the model fits.

Grasset et al. (2009) used the parameterised form

$$\log \left( \frac{R_p}{R_\oplus} \right) = \log \alpha + \left[ \beta + \gamma \frac{M_p}{M_\oplus} + \epsilon \left( \frac{M_p}{M_\oplus} \right)^2 \right] \log \left( \frac{M_p}{M_\oplus} \right), \quad (11.37)$$

where  $\alpha, \beta, \gamma, \epsilon$  are quadratic functions of the mass fraction of water. Over  $1 - 100M_\oplus$ , they estimate 1% accuracy for compositions ranging from Earth-like (essentially zero H<sub>2</sub>O content) to pure ice.

**Other detailed models** Zeng & Sasselov (2013) provided a grid for the mass–radius relation of 3-layer exoplanets between  $0.1 - 100M_\oplus$ , and an interactive tool to illustrate the associated interior structures. The three layers comprise Fe, MgSiO<sub>3</sub> (including the perovskite phase, post-perovskite phase, and its dissociation at ultrahigh pressures), and H<sub>2</sub>O (including ices Ih, III, V, VI, VII, X, and the superionic phase; §11.3.2).

Lopez & Fortney (2014) computed radii for low-mass rocky planets ( $1 - 20M_\oplus$ ) with H–He envelope fractions 0.01–20%, stellar irradiation 0.1–1000 times Earth's, and ages from 100 Myr to 10 Gyr. At fixed H/He envelope fraction, radii show little dependence on mass for planets with  $\geq 1\%$  of their mass in their envelope. Consequently,  $R_p$  is, to first order, a proxy for the H/He envelope fraction for Neptune- and sub-Neptune-sized planets. They suggest  $1.75R_\oplus$  as a physically-motivated dividing line between these two populations.

Based on Bayesian inversion, Dorn et al. (2015) identified what parts of the interior structure of terrestrial exoplanets ( $\leq 10M_\oplus$  and  $\leq 1.7R_\oplus$ ) can be determined from observations of mass, radius, and stellar elemental abundances. They concluded that mass and radius are sufficient to constrain core size; that stellar abundances (Fe, Si, Mg) are principal constraints to reduce degeneracy in interior structure models and to constrain mantle composition; and that the inherent degeneracy in determining interior structure from mass and radius observations depends on the planet's size and density.

A number of structural models (e.g. Seager et al., 2007; Zeng & Seager, 2008; Zeng & Sasselov, 2013) model the cores as a pure  $\epsilon$ -Fe-solid, and the mantles as Mg-perovskite/post-perovskite. A different approach in modeling the mass–radius relation for solid exoplanets (Zeng et al., 2016) has been to build on the known density variations of the Earth's interior derived from measurements of seismic wave velocities, utilising the resulting Preliminary Reference Earth Model (PREM, box, page 533; Dziewonski & Anderson, 1981), and the Birch–Murnaghan second-order equation of state (BM2; Birch, 1952) which describes how material is compressed in the Earth's interior for both core and mantle. Zeng et al. (2016) derived a semi-empirical 2-layer model for  $1 - 8M_\oplus$  and core mass fraction 0.0–0.4 based on an extrapolation of this seismic model

$$\left( \frac{R}{R_\oplus} \right) = (1.07 - 0.21 \cdot \text{CMF}) \left( \frac{M}{M_\oplus} \right)^{1/3.7}. \quad (11.38)$$

This can be inverted to solve for the core mass fraction given the planet's mass and radius

$$\text{CMF} = \frac{1}{0.21} \left[ 1.07 - \left( \frac{R}{R_\oplus} \right) / \left( \frac{M}{M_\oplus} \right)^{1/3.7} \right]. \quad (11.39)$$

Applied to Earth, Venus and several small exoplanets with radii and masses measured to better than 30% yields a core mass fraction fit of  $0.26 \pm 0.07$ . Results are in agreement with the mass–radius relation of super-Earths derived by Valencia et al. (2006), which is a scaling law of  $R \propto M^{0.267-0.272}$ , but accounting for dependence on the CME. It yields, for example, core mass fraction of 0.33 for Earth, and 0.26 for Kepler-93 b.

To facilitate mapping of measured (Kepler) radii to mass estimates in the Earth/Neptune size range where there are no solar system analogues, Wolfgang et al. (2016) derived a probabilistic mass–radius relationship assuming that it can be described as a power law (Equation 11.34) with a dispersion that is constant and normally distributed. They found  $(k, \beta) = (2.7, 1.3)$  for  $R_p < 4R_\oplus$ , with a scatter in mass of  $1.9M_\oplus$ .

For H<sub>2</sub>O-rich interiors, Thomas & Madhusudhan (2016) found that thermal effects induce significant changes in radii: for super-Earths with 10% H<sub>2</sub>O, the radius increases by up to  $0.5R_\oplus$  when the surface temperature increases from 300 to 1000 K, at a surface pressure  $10^7$  Pa. The effects are comparable to current super-Earth radius measurement errors, of  $\sim 0.1R_\oplus$ .

Zeng & Jacobsen (2016) applied the variational principal to planetary interiors to derive a general mass–radius relation, strictly applicable to a 1-layer planet and the BM2 equation of state (approximating the compression of iron alloys and silicates in rocky planetary interiors), as (their Equation 24)

$$\frac{R}{R_\oplus} \approx \left( \frac{(M/M_\oplus)}{(\rho_0/\rho_\oplus)} \left[ 1 + 0.306 \left[ \frac{(\rho_0/\rho_\oplus)^2}{(K_0/200 \text{ GPa})^{3/2}} \frac{M}{M_\oplus} \right]^{0.59} \right]^{-1} \right)^{\frac{1}{3}} \quad (11.40)$$

where  $K_0$  is the bulk modulus at zero pressure.

### 11.5.3 Giant planets

While the radii of many giant planets have been determined from transit measurements, they are typically in short-period orbits ( $a \ll 1$  au), and do not sample the wider populations of gas and ice giants which have formed and reside at the larger separations characteristic of the solar system giants.

For those with estimated masses and radii, there are two complications in characterising their mass–radius relation. The first is that the close-in hot Jupiters ( $T_{\text{eq}} \geq 1000$  K) are found to have inflated radii compared to the predictions of straightforward models of cooling and contraction, and additional (and still uncertain) physics is required to explain them (§6.28.4). A second is that their heavy element content, both in their core and in their envelope, is typically very uncertain (§10.5.1).

**Phase changes** Typically, mass–radius curves are smooth and monotonic, although discontinuities can arise from phase changes. In H-dominated planets at  $\sim 100$  GPa, molecular hydrogen undergoes a phase transition to metallic hydrogen (§11.3.2), leading to a kink in the mass–radius curve at  $M_p \sim 100M_\oplus$  (e.g. Swift et al., 2012; Wilson & Militzer, 2014).

A similar discontinuity occurs with CH<sub>4</sub>, which can dissociate for  $M_p \geq 15M_\oplus$ , leading to the formation of a C (diamond) core, a CH<sub>4</sub> envelope, and a H<sub>2</sub> atmosphere, with a radius significantly larger than that expected without dissociation (Helled et al., 2015). CH<sub>4</sub> dissociation leading to the formation of a C core has also been considered in the context of the solar system giant planets (Ross, 1981; Benedetti et al., 1999).

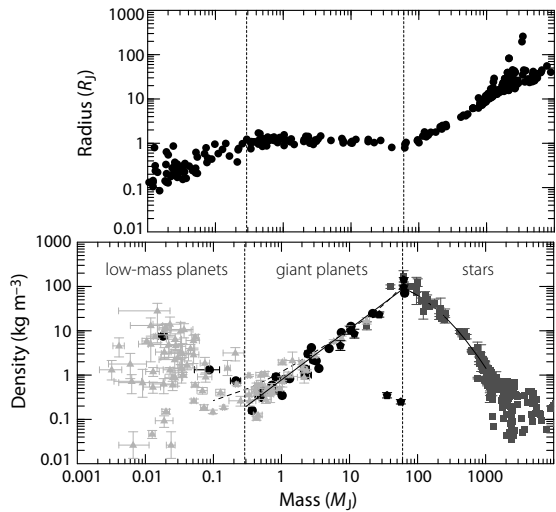


Figure 11.26: Top: well-characterised low-mass planets, giant planets, brown dwarfs, and stars in the mass–radius plane. Bottom: in the mass–density plane, distinguishing stars (grey squares), Kepler discoveries (triangles), CoRoT objects (circles), and ground-based discoveries for high-mass giant planets (pentagons). The solid line is a linear fit over  $0.35 - 60M_J$ . The curved line is a second-order polynomial fit to the lower end of the stellar main sequence. The boundary between low-mass and giant planets is at  $0.3M_J$ , and the boundary between giant planets and stars at  $60M_J \sim 0.06M_\odot$ . The dashed line is the mass–density relation for H/He dominated giant planets from Fortney et al. (2007b). Two outliers in the central region are components of a young eclipsing brown dwarf binary still undergoing gravitational contraction. From Hatzes & Rauer (2015, Figures 1–2), by permission of IOP Publishing/AAS.

### 11.5.4 Mass–density relation

The mass–density relation provides some further insights (Hatzes & Rauer, 2015). From planets ( $\sim 0.01M_J$ ) through stars ( $> 0.08M_\odot$ ), the  $\log M - \log \rho$  relation shows three distinct regions separated by a change in slope (Figure 11.26). There is a broad minimum around  $0.3M_J$  (Rauer et al., 2014; Laughlin & Lissauer, 2015) that separates the H/He-dominated giant planets from low-mass planets of Neptune-mass or smaller, with different slopes in the density–mass plane highlighting the differences in structure between them.

Objects in the range  $0.3 - 60M_J$  follow a tight linear relation with no distinguishing feature separating low-mass objects (giant planets) from high-mass objects (brown dwarfs). The corresponding points in the mass–radius plane shown in the upper part of the figure are part of the wider relation seen in Figure 6.100.

The distinction between giant planets and brown dwarfs seeming arbitrary, they proposed a definition of giant planets based on changes in slope of the  $\log M - \log \rho$  relation. By this criterion, objects with  $M_p \lesssim 0.3M_J$  are low-mass planets, either icy or rocky. Giant planets cover the range  $0.3 - 60M_J$ . Analogous to the stellar main



sequence, objects at the upper end of the giant planet sequence (brown dwarfs) would then be referred to as ‘high-mass giant planet’, while planets with masses near  $1M_J$  would be considered as ‘low-mass giant planets’.

### 11.5.5 Diagnostics from rotation

The limited information on interior structure conveyed by an exoplanet’s mass and radius is augmented, in principle, by the fact that the planet is rotating (Zharkov & Trubitsyn, 1971, 1974, 1978).

In hydrostatic equilibrium, the external gravitational potential at coordinate position  $(r, \theta)$  is given by (Zharkov & Trubitsyn, 1974, eqn 1)

$$V(r, \theta) = \frac{GM_p}{r} \left[ 1 - \sum_{n=1}^{\infty} \left( \frac{R_+}{r} \right)^{2n} J_{2n} P_{2n}(\theta) \right], \quad (11.41)$$

where  $R_+$  is the equatorial radius,  $J_{2n}$  are the planet’s gravitational moments,  $P_{2n}$  are Legendre polynomials, and  $\theta$  is the colatitude. The external gravitational field is then fully specified by the set of gravitational multipole moments (Zharkov & Trubitsyn, 1974, eqn 2)

$$J_{2n} = - \frac{1}{M_p R_+^{2n}} \int \rho(r) r^{2n} P_{2n}(\theta) d\tau, \quad (11.42)$$

where  $\tau$  is a volume element, and the integration extends over the planet’s entire volume.

In the case of the solar system giants (§12.2.2 and Table 12.2), masses are derived from the motions of their natural satellites, radii from radio occultations, and rotation periods are inferred from the time variation of their magnetic fields. All four are relatively fast rotators, with periods 10–11 h for Jupiter and Saturn, and 16–17 h for Uranus and Neptune (§12.4.5). Estimates of  $J_2$  and  $J_4$ , and hence some constraints on their interior density profiles, have been established from the Pioneer and Voyager fly-bys (see Table 12.2 for references).

For exoplanets, where *in situ* measure of the  $J_{2n}$  is not possible, the oblateness may be accessible from transit observations (§6.14.7). It is given in terms of the equatorial and polar radii by (Guillot, 2005, eqn 15)

$$\frac{R_+}{R_+ - R_-} \approx q^{-1} \left( \frac{3}{2} \Lambda_2 + \frac{1}{2} \right)^{-1}, \quad (11.43)$$

where  $\Lambda_2 = (J_2/q) \sim 0.1 - 0.2$ , and where

$$q = \frac{\omega^2 R_+^3}{GM}, \quad (11.44)$$

the ratio of centrifugal acceleration to gravity, provides a measure of rotation rate,  $\omega$ . It may therefore be plausible to obtain the rotation rate from an oblateness measure or, given a rotation rate determined independently, some constraint on their interior structure. Diagnostics of the quadrupole field could be further assisted by additional transiting planets (Becker & Batygin, 2013).

Rapidly rotating and close-in giant planets are marked by the presence of strong zonal flows at cloud level. If sufficiently deep and strong, zonal flows can produce hydrostatic-related gravity anomalies through distortion of the planet’s figure. Hydrostatic models applied to Jupiter suggest that deep zonal flows could contribute up to 0.3% of  $J_2$  (Kong et al., 2012).

For close-in planets, planet rotation can be further disturbed by the tidal torque of the host star, leading to chaotic behaviour around the synchronous rotation state (Callegari & Rodríguez, 2013).

**Rotating fluid planets** For rotating fluid planets, Maclaurin-based models (i.e. due to a self-gravitating fluid body of uniform density, rotating with constant angular velocity) are often used to determine the associated gravitational potential (Hubbard, 2012, 2013b; Kong et al., 2013; Makarov, 2015). The Earth is significantly less oblate than a Maclaurin spheroid, due to its (inhomogeneous) dense iron core.

**Galilean satellites** Gravity measurements from the Galileo mission have similarly been used to construct interior structure and composition models for Jupiter’s Galilean satellites (Sohl et al., 2002). These models provide constraints on the core sizes, and on the mantle densities and possible mineralogies, for example consistent with an olivine-dominated composition in the case of Io and Europa.

For Ganymede, the thickness of the silicate mantle is between 900–1100 km, with an outermost ice shell 900 km thick, further subdivided by pressure-induced phase transitions into ice I, ice III, ice V, and ice VI layers. Bulk Fe/Si ratios suggest a difference in fractionation between the inner (Io, Europa) and outer (Ganymede, Callisto) satellite pairs during formation.

Equilibrium models of heat transfer suggest that Europa, and possibly Ganymede and Callisto, may have oceans underneath their ice shells tens to hundreds of km deep, depending on ice phase, and depending on the degree to which radiogenic is supplemented by tidal heating (Spohn & Schubert, 2003).

## 11.6 Transit and eclipse spectra

This section focuses on the interpretation and results of transit and eclipse spectroscopy, for which the basic principles, including the configurations and observables for primary transit, secondary eclipse, and the full phase curve more generally, are described in Section 6.24.

The central concepts that are involved in their interpretation can be found in the preceding sections, specifically regarding the modeling of giant planet atmospheres, including considerations of chemical composition, temperature profiles, and observational consequences of clouds and hazes (§11.4.1), and regarding general circulation models, including the phenomena of zonal flows and atmospheric superrotation (§11.4.2).

This section introduces the principles of model fitting (§11.6.1), followed by a synopsis of results of current exoplanet transit and eclipse spectroscopy (§11.6.2).

As explained in Section 6.24, current transit and eclipse spectroscopy applies almost exclusively to ‘hot Jupiters’, viz. close-in, short-period, highly irradiated,

gas giants. Some limited observations of the lower-mass but still close-orbiting highly irradiated ‘hot Neptunes’ have also been made. For these reasons, the following focuses mainly on hot Jupiter systems.

In contrast with the atmospheric characterisation of solar system objects (which is facilitated by spatially-resolved observations with long temporal baseline and high signal-to-noise, often augmented by orbiting or fly-by probes with instruments designed for the determination of composition, surface morphologies, magnetic fields, charged-particle environments, and gravitational moments), exoplanets will typically remain as point sources for the foreseeable future, and signal-to-noise will remain an issue. Despite this, a rich variety of physical and chemical processes can be inferred.

### 11.6.1 Data fitting

**Instrument models** In efforts to extract the maximum signal from HST, Spitzer, and other ground-based instruments, parametric models have been widely used to remove instrument systematics (e.g. Tinetti et al., 2013). These aim to replicate systematic noise through the use of auxiliary instrumental information (the *optical state vectors*), which include effects such as positional drifts, focus and detector temperature changes, and position angle on the sky.

**State-of-the-art** New observing modes with HST and Spitzer have progressively improved their data quality, as well as the understanding of residual systematics (Hansen et al., 2014). Improved data analysis techniques to better characterise instrumental noise have been developed (e.g. Waldmann, 2012; Waldmann et al., 2012, 2013; Ingalls et al., 2016; Morello et al., 2016), while statistical extraction techniques developed in cosmology and communication science have also been applied (e.g. Carter & Winn, 2009; Gregory, 2011b; Gibson et al., 2012b).

Despite excellent fits, residuals often exhibit red (time-correlated) noise. The wavelet-based method of Carter & Winn (2009) has been used to estimate the impact of red noise on eclipse depth uncertainties (e.g., the orbit phase curve of HD 189733 b; Knutson et al., 2012), while independent component analysis (Waldmann, 2012) has been used in blind signal de-mixing for transit spectroscopy (Waldmann et al., 2013).

**Data fitting** Retrieval of atmospheric information from integrated broad-band photometry or low-resolution spectroscopy rests on the planet not emitting like a blackbody. Numerous theoretical models have been constructed to aid interpretation of the transit and secondary eclipse fluxes (box, page 591).

A goal of transit and secondary eclipse spectroscopy is to constrain abundances by identifying their signatures in atmospheric spectra, comparing the observed spectrum with spectral models, and retrieving their temperatures and temperature profiles. Since many parameters characterise exoplanet atmospheres (e.g., species, abundances, temperatures, spatial distributions, gravities, cloud and haze layers), the limited information con-

tent of low-resolution spectroscopy or broad-band photometry carries the risk of parameter degeneracy.

Practical approaches in data fitting employ either a traditional self-consistent *radiative transfer* model with a few variables, or the derivative *spectral retrieval* (or *atmospheric retrieval*) model based on a parametric pressure–temperature ( $P - T$ ) profile (Madhusudhan & Seager, 2009). The significance of any detected spectral features or temperature gradients is essentially inferred from the deviation of the eclipse depths as a function of wavelength from a blackbody spectrum.

Spectral retrieval models typically use 10–12 parameters to describe the atmospheric composition and vertical temperature profile. For example, Madhusudhan & Seager (2009) used 6 parameters for the vertical  $P - T$  profile and 4 for molecular abundances. Stevenson et al. (2014b) used 2 additional abundance variables, for a total of 12 model parameters. Lupu et al. (2016) include one or two cloud layers,  $\text{CH}_4$  as a major absorber, and a  $\text{H}_2$ –He background gas, for a total of 6–9 parameters.

**Algorithmic implementation** Numerous algorithms for atmospheric and transmission spectral analysis have been made available, both forward modeling (computing the radiative-convective equilibrium taking into account equilibrium or non-equilibrium chemistry) and retrieval codes (deriving the optimum combination of parameters to reproduce the observations). These include BART, Bayesian Atmospheric Radiative Transfer (Cubillos et al., 2016a); CHIMERA for transmission spectroscopy retrieval (Line et al., 2013b); Exo-REM, the Exoplanet Radiative-convective Equilibrium Model, computing radiative-convective equilibrium (Baudino et al., 2015); Exo-Transmit for calculating transmission spectra (Kempson et al., 2017b); GENESIS, a plane-parallel, self-consistent, line-by-line exoplanetary atmospheric modelling code (Gandhi & Madhusudhan, 2017); HELIOS-Retrieval a nested sampling atmospheric retrieval code (Lavie et al., 2017b; Malik et al., 2017); NEMESIS, for Non-linear optimal Estimator for Multivariate spectral analysis, a retrieval code using the radiative transfer code Radtrans (Irwin et al., 2008b; Barstow et al., 2017); PETIT, Pressure-Temperature Iterator and Spectral Emission Calculator for Planetary Atmospheres (Mollière et al., 2015); PYRATBAY, Python Radiative Transfer in Bayesian Framework (Cubillos et al., 2017d); T-REX or Tau-REX, for transmission and emission spectroscopy (Waldmann et al., 2015b,a); TEA, Thermochemical Equilibrium Abundances (Blecic et al., 2016, 2015); TRANSIT, a radiative-transfer code for planetary atmospheres (Rojo, 2006; Cubillos et al., 2017a); VSTAR, Versatile Software for Transfer of Atmospheric Radiation, incorporating an ionisation and chemical equilibrium model, the treatment of spectral line absorption using a database of  $2.9 \times 10^9$  spectral lines, a scattering package, and a radiative transfer module (Bailey & Kedziora-Chudczer, 2012), and VULCAN, for gaseous chemistry using a reduced C-H-O chemical network (Tsai et al., 2017).

**Colour-magnitude diagrams** The fact that transmission spectroscopy is, to date, typically based on only 2–4 thermal broad-bands, rather than on high-resolution spectroscopy, means that the atmospheric retrieval problem is generally poorly constrained. Accordingly,

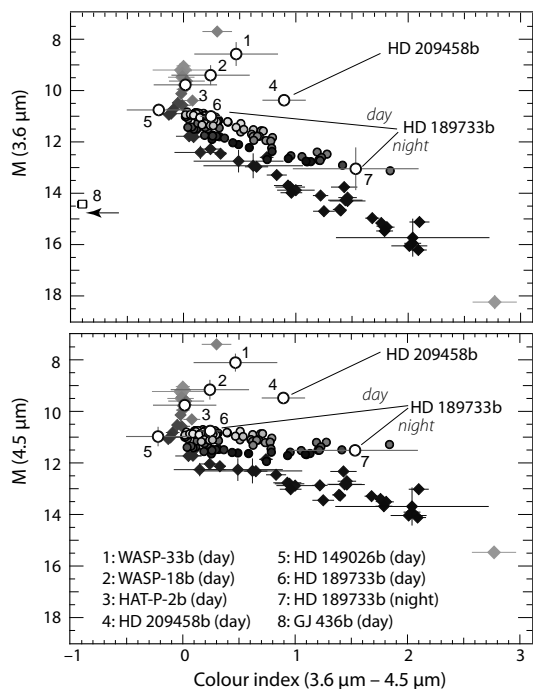


Figure 11.27: Colour–magnitude diagrams of absolute magnitudes at 3.6 and 4.6  $\mu\text{m}$  versus 3.6–4.5  $\mu\text{m}$  colour index. Open circles represent the 7 transiting planets with 3.6 and 4.6  $\mu\text{m}$  fluxes and trigonometric parallax from Hipparcos. Diamonds show the late M dwarfs, L, T, and one Y dwarf compiled by Dupuy & Liu (2012). The kink at  $M(3.6 \mu\text{m}) \sim 11.5$  corresponds to a L9 spectral type, and the location where  $\text{CH}_4$  absorption starts appearing in the 3.6  $\mu\text{m}$  band. Smaller grey circles represent the phase curve of HD 189733b (Knutson et al., 2012), with lighter grey for day-side, and darker tones for night-side. The open square shows the upper limit of GJ 436b. From Triaud (2014, Figure 1), © Oxford University Press.

colour–colour diagrams have been used as an alternative approach to atmospheric classification. When distances are available, apparent magnitudes can be converted to absolute magnitudes, and colour–magnitude diagrams can also be constructed (Baskin et al., 2013; Beatty et al., 2014; Triaud, 2014; Triaud et al., 2014).

Most exoplanet flux measurements have been acquired with Spitzer–IRAC at 3.6 and 4.5  $\mu\text{m}$ , bands that have also been used to observe field brown dwarfs (e.g. Patten et al., 2006; Dupuy & Liu, 2012). The similarity in sizes and temperatures of brown dwarfs and hot Jupiters means that their comparison in colour–colour or colour–magnitude diagrams can provide further insights, exploiting knowledge of field brown dwarf and ultracool star atmospheres acquired over several decades.

As of mid-2014, there were seven systems observed in both 3.6 and 4.5  $\mu\text{m}$  channels that also have Hipparcos parallaxes. All have also been observed by the WISE satellite, whose W1 and W2 bands are close Spitzer–IRAC 3.6 and 4.5  $\mu\text{m}$  channels (Cutri et al., 2012).

Triaud (2014) used these data to show that, in most cases, planets and brown dwarfs follow similar sequences (Figure 11.27). HD 2094589 b and GJ 436 b appear as outliers, as is the night-side of HD 189733 b. HD 189733 b exhibits what appears as a spectral type and chemical transition between its day and night-sides: it straddles the L–T spectral class transition, suggesting different cloud coverage on each hemisphere.  $\text{CH}_4$  absorption could be absent at its hotspot but present over the rest of the planet.

Triaud et al. (2014) extended this work, using photometric distances for 44 transiting exoplanets with flux measurements. They concluded that irradiated planets do not match blackbodies; their emission spectra are not featureless. For a given luminosity, the day-sides of hot Jupiters show a larger variety in colour than brown dwarfs, and display an increasing diversity in colour with decreasing intrinsic luminosity. The presence of an extra absorber within the 4.5  $\mu\text{m}$  band would reconcile outlying hot Jupiters with ultra-cool dwarf atmospheres.

The high-accuracy distances becoming available with Gaia (§3.9) will greatly assist interpretation of the higher resolution emission spectroscopy expected over the coming years with JWST.

### 11.6.2 Results

**Reviews** While the following provides an overview of recent developments, various authoritative reviews over the past 5 years provide other details and perspectives (e.g. Tessenyi et al., 2013; Tinetti et al., 2013; Bailey, 2014; Burrows, 2014b,a; Hansen et al., 2014; Crossfield, 2015; Heng & Showman, 2015; Madhusudhan et al., 2016; Hubeny, 2017; Zhang et al., 2017b; Ehrenreich, 2018).

**NASA Data Archive compilation** The online NASA archive (Table 1.4) provides a compilation of published transmission and emission spectroscopy giving, for each entry, the instrument used, the observation wavelength and bandwidth, the eclipse depth and, for the emission spectra, the inferred brightness temperature.

As of 31 December 2017, the archive lists transmission ‘spectra’ for 78 planets (71 host stars, including 6 with more than one planet observed). These include 9 HAT, 30 Kepler, and 17 WASP systems. Transit depths exceed 1.5% for HD 189733, WASP–17, WASP–19, WASP–43, and XO–1. Emission ‘spectra’ are listed for 46 planets, including 9 HAT, 4 TreES, 18 WASP, and 4 XO systems. Eclipse depths exceed 0.5–1% in the case of CoRoT–2, HD 189733, WASP–12, WASP–19, and WASP–80.

**Scientific inferences** The transit and secondary eclipse spectroscopy and photometry acquired to date relate principally to transiting hot Jupiters. As detailed in the preceding, these data are nonetheless starting to provide insights into atmospheric structure and circulation, atomic and molecular species, and the presence of clouds and hazes.

Results are given first for the two best observable systems known, HD 189733 and HD 209458. This is followed by a summary of results from transit, eclipse, and phase curve observations for other systems.

**HD 189733** HD 189733 is a bright ( $V = 7.7$ ) K0 star at  $d = 19$  pc, which hosts a close-orbiting ‘hot Jupiter’ planet, HD 189733 b. From radial velocity and transit observations, the planet ( $M_p = 1.15M_J$ ,  $R_p = 1.26R_J$ ), orbits the  $M_\star = 0.80M_\odot$ ,  $R_\star = 0.79R_\odot$  star at a distance of  $a = 0.031$  au (i.e.  $\sim 8.75R_\star$ ), and with an orbital period  $P = 2.219$  d, much smaller than the stellar rotational period; a more accurate period  $P = 2.218574(8)$  d was determined from its *a posteriori* transit detection in the Hipparcos epoch photometry (§6.10.3). The orbit is nearly circular, and the orbital plane is aligned to within a few degrees of the Earth–primary line-of-sight. The host star appears to be one component of a binary star system (accordingly more strictly denoted HD 189733A), the secondary being an M dwarf at a projected distance of 216 au and  $P_{\text{orb}} \sim 3200$  yr (Bakos et al., 2006b).

Like HD 209458, HD 189733 is one of most intensively observed transiting planet on account of its brightness, favourable geometry, its large transit depth ( $\sim 2.5\%$ ), its proximity, and its short orbital period.

HD 189733 was the first hot Jupiter for which characterisation of the day-side and night-side temperatures was established over a significant fraction of the planet’s orbit. Based on  $Q$  values for giant planets in the solar system, it had already been concluded that at orbital radii of a few  $\times 0.01$  au from their parent star, tidal dissipation time scales for hot Jupiters should be at most a few Myr, such that tidally-locked hot Jupiters should be the norm. Under this hypothesis, HD 189733 b might be expected show a pronounced temperature difference between the day-side and night-side hemispheres.

Knutson et al. (2007a) followed the flux over over half an orbital period, and constructed a longitudinal map of the temperature distribution as the day-side of the planet rotated into view. They estimated minimum and maximum brightness temperatures of  $973 \pm 33$  K and  $1212 \pm 11$  K at  $\lambda = 8 \mu\text{m}$ , a relatively small difference suggesting that energy from the irradiated day-side is efficiently redistributed throughout the atmosphere. Their data indicated that the peak hemisphere-integrated brightness is displaced by  $16 \pm 6^\circ$  east longitude with respect to the substellar point (Figure 11.28). This type of observation has since been carried out for a number of other hot Jupiters (§11.6.3).

A chronological summary of the main observational efforts to characterise the atmospheric properties of HD 189733 through transit and eclipse measurements is given in Table 11.5. The table gives an indication of the instruments and wavelengths that have been used (notably HST and Spitzer), the chemical species identified, and some of the controversies that have accompa-

nied their interpretation and re-analysis. A more complete bibliography, include more detailed modeling, is given in Appendix D. More details of the progress in atmospheric characterising are given in the introductions to several of these papers.

As an example of these spectral measurements, Figure 11.29 shows the Spitzer infrared measurements of the secondary eclipse depths over  $3.6\text{--}24 \mu\text{m}$ . These measurements were used to infer the presence of both  $\text{H}_2\text{O}$  and  $\text{CO}$  in the planet atmosphere (Charbonneau et al., 2008, Figure 11.30). Observations over  $1.5\text{--}2.5 \mu\text{m}$  by Swain et al. (2008b), suggest both the presence of  $\text{H}_2\text{O}$  and  $\text{CH}_4$  in the atmosphere (Figure 11.31).

A distinctive slope in the transmission spectrum of HD 189733 b, measured with HST-ACS and STIS, demonstrated that  $R_p$  decreases by 1.5% between  $345\text{--}775$  nm (Pont et al., 2008a; Sing et al., 2011b). This has been attributed to Rayleigh scattering by hazes at  $T \sim 1300$  K, possibly increasing to 2000 K at the shortest wavelengths, which probe the lowest pressure region of the atmosphere (Lecavelier des Etangs et al., 2008a; Pont et al., 2013; B  tr  mieux, 2016). The signature of Rayleigh scattering can be affected by refraction (§6.14.11).

As an example of the difficulties of atmospheric characterisation encountered, the day-side emission spectrum was characterised as featureless by Grillmair et al. (2007), found to exhibit absorption features by Grillmair et al. (2008), and line emission by Swain et al. (2010a), but unconfirmed by Mandell et al. (2011).

**HD 209458** HD 209458 is a bright ( $V = 7.7$ ) G0V star at  $d = 47$  pc. From radial velocity observations the planet, with  $M_p = 0.69M_J$ , is known to orbit the  $M_\star = 1.01M_\odot$  star at a distance of 0.047 au. Its accurate orbital period of 3.524 748 59 d was determined after *a posteriori* detection in the Hipparcos epoch photometry (Robichon & Arenou, 2000). It was the first known transiting planet, initially observed at modest signal-to-noise with small-diameter discovery instruments by Henry et al. (1999, 2000) and independently by Charbonneau et al. (2000, see Figure 6.1).

The system’s proximity and brightness, the planet’s close-in orbit, and its large transit depth of  $\sim 2\%$  make it one of the most observed transiting planets. Availability of a planet radius and mass, an age from stellar evolution theory, and a luminosity from its trigonometric parallax, combine to make it valuable for theoretical study.

HST gave a much improved transit light curve (Figure 6.15), from which Brown et al. (2001) derived  $R = 1.35R_J$  from the transit decrement. The large radius for such a small mass (§6.25) showed that these massive close-orbit planets were not rocky cores, but large, Jupiter-sized objects. Its density  $\rho_p = 0.35 \text{ Mg m}^{-3}$ , surface gravity  $g_p = 9.43 \text{ m s}^{-2}$ , and escape velocity  $v_e = 43 \text{ km s}^{-1}$ , also indicate that the planet is stable against disruption by tidal forces, thermal evaporation, or mass

Table 11.5: Observations of HD 189733 focusing on atmospheric characterisation through new observations or re-analysis, ordered by publication date, through to the end of 2017 (a more complete bibliography, include more detailed modeling, is given in Appendix D). Under ‘Type’ of observation is listed the number of transits ( $T$ ), or eclipses ( $E$ ) observed.

Instrument	Type	Wavelength	Results	Reference
Spitzer–IRS	1E	16 $\mu\text{m}$	strong thermal emission	Deming et al. (2006)
Spitzer–IRS	1T	7.5–14.7 $\mu\text{m}$	limit on H <sub>2</sub> O, CH <sub>4</sub> ; efficient heat distribution	Grillmair et al. (2007)
various	8T	optical	$R_p = 1.154R_J$ , $\rho = 0.91 \text{ Mg m}^{-3}$ , $g_p = 9.28 \text{ m s}^{-2}$	Winn et al. (2007c)
Spitzer–IRAC	1T/1E	8 $\mu\text{m}$	small day/night temperature range, 973–1212 K	Knutson et al. (2007a)
CHARA	–	1.67 $\mu\text{m}$	$R_p = 1.19R_J$ directly from $R_* = 0.779R_\odot$	Baines et al. (2007)
Spitzer–IRAC	2T	3.6, 5.8, 8 $\mu\text{m}$	absorption by H <sub>2</sub> O inferred (re-analysis)	Tinetti et al. (2007b)
Spitzer–IRAC	1T	3.5, 5.8 $\mu\text{m}$	limit on H <sub>2</sub> O	Ehrenreich et al. (2007)
Keck–NIRSPEC	1T	2.0–2.4 $\mu\text{m}$	limit on H <sub>2</sub> O and CO absorption	Barnes et al. (2007a)
HST–ACS	3T	550–1050 nm	$R_p = 1.154R_J$ , $i = 85^\circ 68$ , spots, no moons	Pont et al. (2007a)
Spitzer–IRS	1T	7.5–14.7 $\mu\text{m}$	detection of H <sub>2</sub> O absorption (re-analysis)	Tinetti et al. (2007b)
HET–HRS	11T	500–900 nm	Na I doublet lines	Redfield et al. (2008)
Spitzer	–	–	H <sub>2</sub> O from models; day–night transfer = 43%	Barman (2008)
HST–ACS	3T	550–1050 nm	featureless spectrum suggests hazy clouds	Pont et al. (2008a)
HST–NICMOS	1T	1.5–2.5 $\mu\text{m}$	CH <sub>4</sub> at 2.2 $\mu\text{m}$ , resolved H <sub>2</sub> O at 1.9 $\mu\text{m}$	Swain et al. (2008b)
Spitzer–IRAC	1T	3.6, 5.8 $\mu\text{m}$	H <sub>2</sub> O in upper atmosphere	Beaulieu et al. (2008)
HST–ACS	3T	550–1050 nm	MgSiO <sub>3</sub> grains of 0.1–0.01 $\mu\text{m}$ (re-analysis)	Lecavelier et al. (2008)
Spitzer–IRAC	2E	3.6–24 $\mu\text{m}$	4 $\mu\text{m}$ low-opacity emission, no inversion	Charbonneau et al. (2008)
Spitzer–IRS	10E	3.6–24 $\mu\text{m}$	H <sub>2</sub> O vibration (6–6.5 $\mu\text{m}$ ), possible CO (4.5 $\mu\text{m}$ )	Grillmair et al. (2008)
Spitzer–IRAC	2T	3.6–8 $\mu\text{m}$	improved $R_p/R_*$ ratios, no H <sub>2</sub> O at 5.8 $\mu\text{m}$	Désert et al. (2009)
HST–NICMOS	5T	1.66, 1.87 $\mu\text{m}$	Raleigh scattering by sub- $\mu\text{m}$ haze particles	Sing et al. (2009)
Spitzer–MIPS	1T/1E	24 $\mu\text{m}$	constraints on day–night circulation	Knutson et al. (2009c)
HST–NICMOS	1E	1.5–2.5 $\mu\text{m}$	H <sub>2</sub> O, CO, CO <sub>2</sub> to explain day-side spectrum	Swain et al. (2009c)
Spitzer–IRAC	1T	3.6, 5.8 $\mu\text{m}$	no H <sub>2</sub> O, constraints on CO	Désert et al. (2009)
Spitzer–IRAC	6T/6E	8 $\mu\text{m}$	atmospheric modeling, constraints on variability	Agol et al. (2010)
Keck–NIRSPEC	1E	2.0–2.4 $\mu\text{m}$	constraints on H <sub>2</sub> O and others	Barnes et al. (2010)
IRTF–SpeX	1E	2.0–4.1 $\mu\text{m}$	possible detection of CH <sub>4</sub>	Swain et al. (2010a)
Spitzer–IRAC	1T	3.6 $\mu\text{m}$	Rayleigh scattering by haze	Désert et al. (2011d)
HST–NICMOS	1T	1.5–2.5 $\mu\text{m}$	no detection of H <sub>2</sub> O, CH <sub>4</sub> , CO <sub>2</sub> (re-analysis)	Gibson et al. (2011b)
Keck–NIRSPEC	1E	3.25 $\mu\text{m}$	non-detection of $L$ -band emission	Mandell et al. (2011)
HST–STIS	1T	290–570 nm	Rayleigh scattering by high-altitude haze	Sing et al. (2011b)
HST–STIS	2T	119–125 nm	variations in Ly- $\alpha$	Lecavelier et al. (2012)
HET–HRS	1T	650–665 nm	H $\alpha$ absorption	Jensen et al. (2012)
Spitzer–IRAC	6T/8E	8 $\mu\text{m}$	evidence for atmospheric hot spot (re-analysis)	de Wit et al. (2012)
IRTF–SpeX	3E	3.3 $\mu\text{m}$	evidence for CH <sub>4</sub>	Waldmann et al. (2012)
Spitzer–IRAC	1E	8 $\mu\text{m}$	longitudinal offset of day-side hot spot	Majeau et al. (2012)
HST–STIS	7T	581–638 nm	pressure–temperature profile from Na I	Huitson et al. (2012)
HST–COS	1T	130 nm	detection of neutral oxygen (re-analysis)	Ben-Jaffel & Ballester (2013)
VLT–CRIRES	1T	2–2.3 $\mu\text{m}$	detection of CO in day-side; no H <sub>2</sub> O, CO <sub>2</sub> , CH <sub>4</sub>	de Kok et al. (2013)
Keck–NIRSPEC	1E	2.27–2.38 $\mu\text{m}$	detection of CO absorption (re-analysis)	Rodler et al. (2013a)
VLT–CRIRES	1E	3.2 $\mu\text{m}$	H <sub>2</sub> O absorption in day-side atmosphere	Birkby et al. (2013)
various	–	–	assessment and confirmation of CH <sub>4</sub> detection	Swain et al. (2014)
IRTF–SpeX	1T	0.94–2.42 $\mu\text{m}$	weak evidence for H <sub>2</sub> O	Danielski et al. (2014)
Spitzer–IRAC	2T	3.6 $\mu\text{m}$	re-evaluation of transit observations (re-analysis)	Morello et al. (2014)
HST–WFC3	1T	1.1–1.7 $\mu\text{m}$	Rayleigh scattering; marginal H <sub>2</sub> O at 1.15 and 1.4 $\mu\text{m}$	McCullough et al. (2014a)
HST–WFC3	1E	1.1–1.7 $\mu\text{m}$	Rayleigh scattering; marginal H <sub>2</sub> O at 1.15 and 1.4 $\mu\text{m}$	Crouzet et al. (2014)
HST–WFC3	1T	1.1–1.7 $\mu\text{m}$	confirmation of H <sub>2</sub> O at 20–135 $\times$ sub-solar	Madhusudhan et al. (2014b)
ESO–HARPS	1T	380–690 nm	spectrally resolved detection of Na	Wyttenbach et al. (2015)
SOFIA	1T	$B$ , $z'$ , 1.88 $\mu\text{m}$	limits on star spot confusion	Angerhausen et al. (2015b)
Keck–HIRES	2T	optical	H-absorption consistent with thin leading bow shock	Cauley et al. (2015)
ESO–HARPS	1T	optical	spatially resolved eastward winds and planet rotation	Louden & Wheatley (2015)
VLT–CRIRES	1T	2.3 $\mu\text{m}$	planet rotation and winds from CO and H <sub>2</sub> O absorption	Brogi et al. (2016)
HARPS+HIRES	7T	optical	H $\alpha$ transmission versus stellar activity, 2006–15	Cauley et al. (2017a)
VLT–UVES	1T	330–700 nm	time-resolved photometry of a stellar flare	Klocová et al. (2017)

stripping by the stellar wind.

Estimates of  $M_*$ ,  $R_*$ ,  $M_p$ ,  $R_p$  have been revised as improved stellar models, and improved transit light curves and orbit analyses, have been applied. The mass–radius relation continues to be a topic of investigation.

From the wavelength dependence of the estimated transit radius, the presence of neutral Na in the atmosphere was inferred (Charbonneau et al., 2002). Limits on CO (Brown et al., 2002), H<sub>2</sub>O (Richardson et al., 2003a), and CH<sub>4</sub> (Richardson et al., 2003b) followed.

The existence of an extended and escaping gaseous envelope, or exosphere, resulting from high temperatures in its upper atmosphere, was invoked to explain strong atomic hydrogen absorption (Vidal-Madjar et al., 2003). The resulting mass loss is, nevertheless, only 0.1% over the age of the system. C and O are also present in the exosphere (Vidal-Madjar et al., 2004), but since both are too heavy to be lost by Jean’s escape, their presence was attributed to hydrodynamic loss in which the heavier elements are carried by outflowing hydrogen.

Table 11.6: Observations of HD 209458 focusing on atmospheric characterisation through new observations or re-analysis, ordered by publication date, through to the end of 2017. A more complete bibliography, including more detailed modeling, is given in Appendix D. Under ‘Type’ of observation is listed the number of transits ( $T$ ), or eclipses ( $E$ ) observed.

Instrument	Type	Wavelength	Results	Reference
APT 0.8-m	1T	<i>by</i>	$R_p = 1.42R_J$ , $\rho = 0.27 \text{ Mg m}^{-3}$	Henry et al. (1999, 2000)
STARE 0.1-m	2T	<i>R</i>	$R_p = 1.27R_J$ , $g_p = 9.7 \text{ m s}^{-2}$ , $\rho = 0.38 \text{ Mg m}^{-3}$	Charbonneau et al. (2000)
Hawaii 2.2-m	1T	400–800 nm	$R_p = 1.55R_J$	Jha et al. (2000)
Sierra Nevada 0.9-m	1T	<i>uvby</i>	derivation of limb darkening	Deeg et al. (2001)
HST-STIS	4T	582–638 nm	$R_p = 1.347R_J$ , $i = 86^\circ 6$ , $\rho = 0.35 \text{ Mg m}^{-3}$	Brown et al. (2001)
VLT-UVES	1T	328–699 nm	limit on exosphere	Moutou et al. (2001)
HST-STIS	4T	589.3 nm	detection of Na, $\delta\Delta = 2.3 \times 10^{-4}$ (re-analysis)	Charbonneau et al. (2002)
Keck–NIRSPEC	1T	2–2.5 $\mu\text{m}$	limit on CO	Brown et al. (2002)
VLT-ISAAC	2E	3.6 $\mu\text{m}$	limit on CH <sub>4</sub>	Richardson et al. (2003b)
IRTF–SpeX	2E	1.9–4.2 $\mu\text{m}$	limits on CO and H <sub>2</sub> O	Richardson et al. (2003a)
HST-STIS	3T	121.5 nm	detection of H Ly- $\alpha$ in an extended exosphere	Vidal-Madjar et al. (2003)
VLT-ISAAC	1T	1080 nm	limit on He I	Moutou et al. (2003)
HST-STIS	4T	118–171 nm	H I + O I, C II due to hydrodynamic escape	Vidal-Madjar et al. (2004)
Subaru–HDS	1T	410–680 nm	limit on H $\alpha$	Winn et al. (2004b)
Spitzer–MPIS	1E	24 $\mu\text{m}$	thermal emission $T \approx 1130 \text{ K}$ , implies irradiation	Deming et al. (2005b)
Keck–NIRSPEC	3T	2 $\mu\text{m}$	limit on CO	Deming et al. (2005a)
Subaru–HDS	2T	410–680 nm	limit on Na, Li, H $\alpha/\beta/\gamma$ , Fe, Ca	Narita et al. (2005)
Lick/Keck Doppler	–	–	probable eccentricity, $e = 0.014 \pm 0.009$	Laughlin et al. (2005b)
UKIRT 3.8-m	2E	2.2 $\mu\text{m}$	limit on secondary eclipse	Snellen (2005)
Various	–	–	improved orbit: $R_p = 1.35R_J$ , $M_p = 0.66M_J$	Wittenmyer et al. (2005)
MOST	4T/4E	400–700 nm	albedo $p(\lambda) < 0.25$	Rowe et al. (2006)
Spitzer–MPIS	2T	24 $\mu\text{m}$	$R_p = 1.26R_J$ (for $M_\star = 1.17R_\odot$ , $R_\star = 1.06R_\odot$ )	Richardson et al. (2006)
HST-STIS	4T	290–1030 nm	limb darkening, $R_p = 1.32R_J$ , transit time limits	Knutson et al. (2007c)
HST-STIS	1T	300–550 nm	hot H: dense atmosphere of 5000 K at 8000 km	Ballester et al. (2007)
Spitzer–IRS	2E	7.5–13.2 $\mu\text{m}$	emission at 7.8/9.6 $\mu\text{m}$ , possibly silicate clouds	Richardson et al. (2007)
MOST	15T	optical	limit on other planets and Trojans at $\approx 2 - 4M_\oplus$	Croll et al. (2007a)
IRTF	2E	3.8 $\mu\text{m}$	limit on secondary eclipse from the ground	Deming et al. (2007b)
HST-STIS	4T	290–1030 nm	water absorption from models (re-analysis)	Barman (2007)
HST-STIS	4T	582–638 nm	surface gravity $g_p = 9.28 \text{ m s}^{-2}$ (re-analysis)	Southworth et al. (2007)
Spitzer–IRAC	1E	3.6–8 $\mu\text{m}$	atmospheric temperature inversion	Knutson et al. (2008)
Spitzer–IRS	2E	7.5–13.2 $\mu\text{m}$	emission at 7.5–8.5 $\mu\text{m}$ (re-analysis)	Swain et al. (2008a)
HST-ACS	2T	Ly- $\alpha$	confirmation of exospheric H	Ehrenreich et al. (2008)
Subaru–HDS	1T	410–680 nm	confirmation of Na from HST (re-analysis)	Snellen et al. (2008)
Spitzer	2T	24 $\mu\text{m}$	$R_p = 1.275R_J$ using $e = 0.014$ (re-analysis)	Kipping (2008)
HST-STIS	T	552–638 nm	confirmation of Na	Sing et al. (2008a)
HST-STIS	5T	290–1030 nm	TiO and VO from models (re-analysis)	Désert et al. (2008)
MOST	15T	optical	albedo $p < 0.08$	Rowe et al. (2008)
HST-NICMOS	1E	1.5–2.5 $\mu\text{m}$	CH <sub>4</sub> , H <sub>2</sub> O, CO <sub>2</sub> ; temperature inversion	Swain et al. (2009b)
HST-STIS	T	ultraviolet	thermosphere in the ultraviolet (re-analysis)	Koskinen et al. (2010b)
Spitzer–IRAC	1T	3.6–8.0 $\mu\text{m}$	atmospheric H <sub>2</sub> O	Beaulieu et al. (2010b)
HST	nT	580–600 nm	pressure–temperature from Na D (re-analysis)	Vidal-Madjar et al. (2011)
Various	–	–	CH <sub>4</sub> , NH <sub>3</sub> , and HCN (re-analysis)	Moses et al. (2011)
HST-COS	1T	115–320 nm	detection of C II and Si III	France et al. (2011)
Spitzer–MIPS	3E/2T	24 $\mu\text{m}$	transit and eclipse parameters	Crossfield et al. (2012c)
HET-HRS	1T	650–670 nm	evidence for H $\alpha$ absorption	Jensen et al. (2012)
Subaru–HDS	nT	410–680 nm	detection of Ca, and possibly Sc and H	Astudillo-Defru & Rojo (2013)
HST-NICMOS	1T	1.2–2.5 $\mu\text{m}$	H <sub>2</sub> O absorption at 200 ppm at 1.38 $\mu\text{m}$	Deming et al. (2013)
HST-STIS	1T	near UV	detection of atomic Mg	Vidal-Madjar et al. (2013)
Spitzer–IRAC	1T/2E	4.5 $\mu\text{m}$	full phase curve with shift of planet hot spot	Zellem et al. (2014b)
HST-WFC3	1T	1.1–1.7 $\mu\text{m}$	H <sub>2</sub> O abundance	Madhusudhan et al. (2014b)
IRTF–SpeX/Hale	1E	1.6, 2.2, 3.5 $\mu\text{m}$	limits from ground infrared emission spectra	Zellem et al. (2014a)
Spitzer–IRAC	4E	3.6–8.0 $\mu\text{m}$	no evidence for thermal inversion (re-analysis)	Diamond-Lowe et al. (2014)
VLT-CRIRES	3E	2.3 $\mu\text{m}$	no evidence for thermal inversion, limit on CO	Schwarz et al. (2015a)
HST-COS	1T	115–320 nm	no evidence for Si III (re-analysis)	Ballester & Ben-Jaffel (2015)
HST-WFC3	1E	1.1–1.7 $\mu\text{m}$	no thermal inversion	Line et al. (2016)
VLT-UVES	1T	330–700 nm	spatially-resolved spectroscopy across the stellar surface	Dravins et al. (2017b)

A chronology of observational efforts to characterise the atmospheric properties of HD 209458 through transit and eclipse measurements is given in Table 11.6. The table gives an indication of the instruments and wavelengths that have been used (notably HST and Spitzer), the chemical species identified, and some of the controversies that have accompanied their interpretation and re-analysis. A more complete bibliography, includ-

ing modeling, is given in Appendix D. Progress in atmospheric characterisation are given in the introductions to several papers (e.g. Moses et al., 2011).

HST and Spitzer observations have been interpreted as indicating the presence of silicate clouds (Richardson et al., 2007), H<sub>2</sub>O (Barman, 2007), TiO and VO absorption (Désert et al., 2008), CH<sub>4</sub>, H<sub>2</sub>O and CO<sub>2</sub> (Swain et al., 2009b), and the existence of an atmospheric

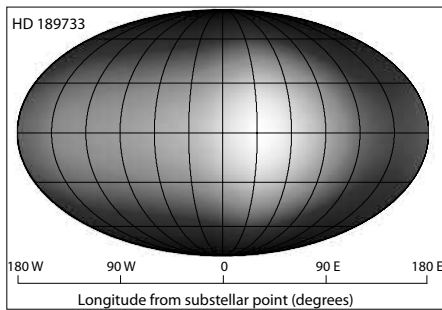


Figure 11.28: HD 189733, observed with Spitzer-IRAC at  $8\ \mu\text{m}$ , showing brightness estimates for twelve longitudinal strips on the planet surface. The planet is assumed tidally locked, edge-on, and with no limb-darkening. A sinusoidal dependence on longitude has been added. From Knutson et al. (2007a, Figure 3), by permission from Nature/Springer/Macmillan Ltd, ©2007.

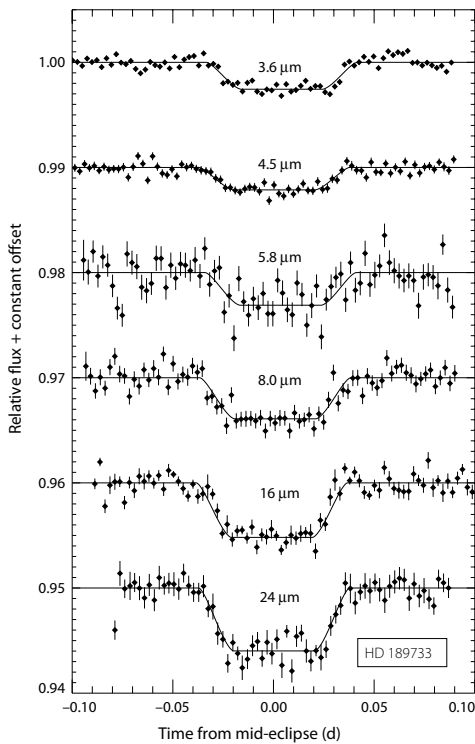


Figure 11.29: HD 189733: Spitzer time series observations over  $3.6\text{--}24\ \mu\text{m}$ , including best-fit eclipse curves. Each time series is binned in 3.5-min intervals, normalised, and plotted with a distinct constant offset. From Charbonneau et al. (2008, Figure 2), by permission of IOP Publishing/AAS.

temperature inversion resulting from high-altitude absorbers (Knutson et al., 2008; Swain et al., 2009b). As an example of these observations, the  $4.5\ \mu\text{m}$  phase curve of HD 209458, obtained with Spitzer-IRAC by Zellem et al. (2014b), is shown in Figure 11.32.

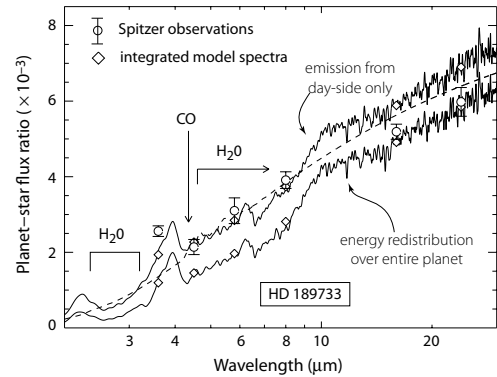


Figure 11.30: HD 189733: Spitzer-observed  $3.6\text{--}24\ \mu\text{m}$  eclipse depths (circles). Models assume either that emission of the absorbed stellar flux is constrained to the day-side only (upper curve), or uniformly redistributed over the planet (lower curve). Diamonds are synthetic spectra integrated over the Spitzer bandpasses. The flux ratio of a black-body spectrum with  $T = 1292\ \text{K}$  is shown dashed. From Charbonneau et al. (2008, Figure 3), by permission of IOP Publishing/AAS.

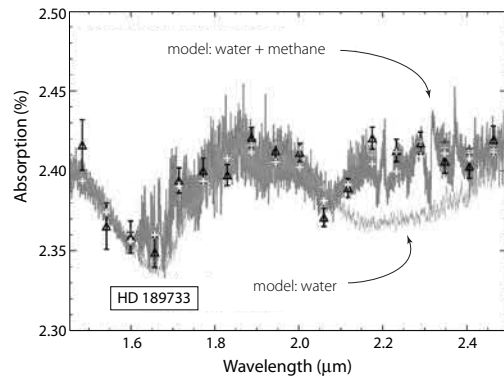


Figure 11.31: HD 189733: HST-NICMOS transit observations over  $1.5\text{--}2.5\ \mu\text{m}$  ( $\blacktriangle$ ). Theoretical spectra of the predominantly  $\text{H}_2$  atmosphere show the effects of water at an abundance of  $5 \times 10^{-4}$  (lower), and improved fits at  $1.7\text{--}1.8\ \mu\text{m}$  and  $2.15\text{--}2.4\ \mu\text{m}$  with an additional  $\text{CH}_4$  abundance of  $5 \times 10^{-5}$  (upper). [The model can be improved with the addition of small amounts of either  $\text{NH}_3$  or  $\text{CO}$ .] From Swain et al. (2008b, Figure 2), by permission from Nature/Springer/Macmillan Ltd, ©2008.

**Other results from transit spectra** Transit observations from space, with HST-STIS/COS/WFC3, and from the ground, have provided a variety of results. They have demonstrated elements and ions (including H, C, O, Ca II) enveloping and escaping from various planets (via Jeans and/or hydrodynamic escape, §11.4.5). Such behaviour has been seen in HD 209458 b (e.g. Vidal-Madjar et al., 2003, 2004; Ben-Jaffel, 2007, 2008; Ben-Jaffel & Sona Hosseini, 2010; Linsky et al., 2010; Jensen et al., 2012); in HD 189733 b (e.g. Lecavelier des Etangs et al., 2010, 2012; Jensen et al., 2012); and in WASP-12 b (Fossati et al., 2010b).

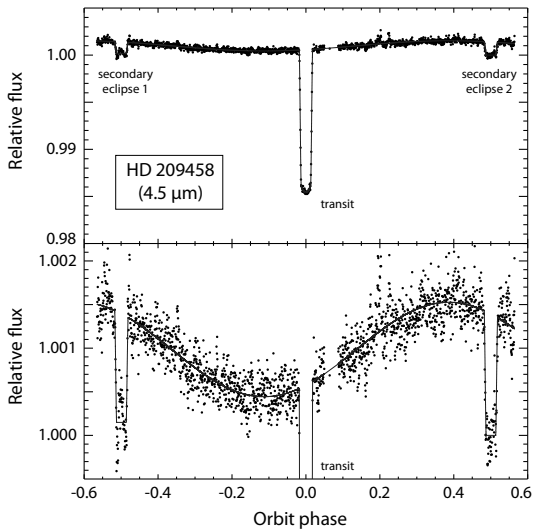


Figure 11.32: Phase curve of HD 209458 b at  $4.5\ \mu\text{m}$  observed with *Spitzer*–*IRAC*. Increased scatter just prior to the first secondary eclipse, in the middle of the first secondary eclipse, and at phase 0.2 are likely due to residual systematic errors or possibly stellar activity. From Zellem et al. (2014b, Figure 2), by permission of IOP Publishing/AAS.

After the discovery of Na in the atmosphere of HD 209458 b (Charbonneau et al., 2002; Snellen et al., 2008), other measurements of alkali metals have been reported, from space and the ground, amongst them Na in HD 189733 b (Redfield et al., 2008), and WASP–17 b (Wood et al., 2011), and K in XO–2 b (Sing et al., 2011a). For some planets, the alkali metal abundances appear to be greatly depleted relative to solar, and attributed to the presence of clouds or to photoionisation. Atreya et al. (2003) suggested that, rather than being primordial, the observed alkali metals may be largely of non-planetary origin, i.e. from debris, meteorites and comets.

In the visible, hazes or clouds of unknown composition have been inferred to affect the transparency of HD 209458 (Barman, 2007), HD 189733 (Knutson et al., 2007a; Pont et al., 2008a; Sing et al., 2011b), and WASP–12 (Sing et al., 2013; Stevenson et al., 2014c,b).

A number of planets, such as GJ 436 (Knutson et al., 2014a) and GJ 1214 (Kreidberg et al., 2014b) show flat featureless transit spectra. In general, these may result from either an atmosphere of high mean molecular weight (and thus small scale height, cf. Equation 6.154), or from high-altitude clouds or hazes (§11.4.1), of the form inferred for the atmospheres of some hot Jupiters (noted above). GJ 1214 b is discussed further below.

In the near-infrared, distinctive molecular features are seen in XO–1 b (Tinetti et al., 2010; Deming et al., 2013), XO–2 b (Crouzet et al., 2012), WASP–12 b (Swain et al., 2013), HD 209458 b (Deming et al., 2013), and HD 189733 b (Danielski et al., 2014).

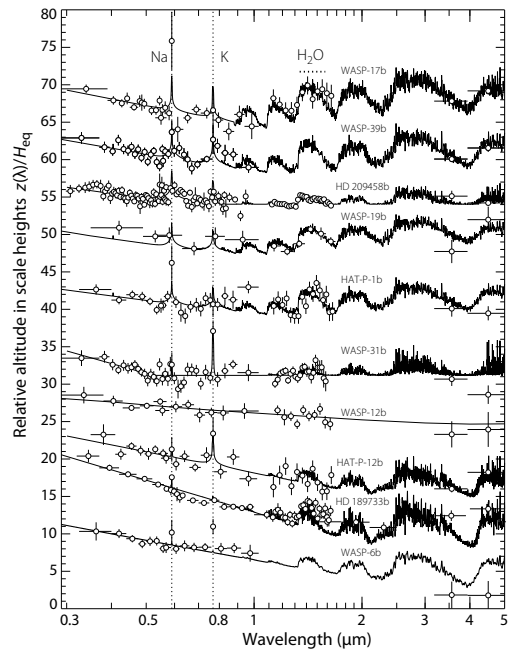


Figure 11.33: *HST/Spitzer* transmission spectral sequence of 10 hot Jupiters. Solid lines show fitted atmospheric models with prominent spectral features indicated. The spectra have been offset, ordered by the altitude difference between the blue-optical and mid-infrared. Planets with predominantly clear atmospheres (top) show prominent alkali and  $\text{H}_2\text{O}$ -absorption, with infrared radii values commensurate or higher than the optical altitudes. Heavily hazy and cloudy planets (such as WASP–6 b and HAT–P–12 b, bottom) have strong optical scattering slopes, narrow alkali lines and  $\text{H}_2\text{O}$ -absorption that is partially or completely obscured. Planets such as WASP–39 b show prominent alkali absorption lines with pressure-broadened wings, whereas others such as WASP–31 b show strong but narrow alkali features, implying they are limited to lower atmospheric pressures. From Sing et al. (2016, Figure 1) by permission from Nature/Springer/Macmillan Ltd, ©2016.

Uniform analyses of some 20 near-infrared transmission spectra with *HST*–*WFC3* which, at  $1.1$ – $1.7\ \mu\text{m}$ , probe primarily the  $\text{H}_2\text{O}$  absorption band at  $1.4\ \mu\text{m}$ , suggest  $\text{H}_2\text{O}$  detection for at least half (Wakeford et al., 2016; Iyer et al., 2016; Fu et al., 2017a).

In a comparative study of ten hot Jupiters over  $0.3$ – $5\ \mu\text{m}$ , spanning different levels of  $\text{H}_2\text{O}$ -absorption features in their near-infrared spectra, Sing et al. (2016) resolved both the optical scattering continuum and infrared molecular absorption (Figure 11.33). They found that the difference in  $R_p$  measured at optical and infrared wavelengths correlates with the spectral strength of water, with strong  $\text{H}_2\text{O}$ -absorption lines in those with clear atmospheres, and the weakest features associated with clouds and hazes. Their results suggests that primordial water depletion during formation is an unlikely explanation for low  $\text{H}_2\text{O}$ -absorption strengths seen in some objects, and that clouds and hazes are the likely



Table 11.7: Properties of the transiting planets modeled by Kataria et al. (2016). Values for  $R_p$ ,  $T_{\text{orb}} = T_{\text{rot}}$  (for synchronous rotation), atmospheric rotation rate  $\Omega$ , surface gravity  $g$ , equilibrium temperature  $T_{\text{eq}}$ , stellar flux  $F_\star$ , and atmospheric pressure scale height  $H$  are from Sing et al. (2016). Values for the Rossby number  $Ro$ , expected number of atmospheric jets  $N_{\text{jets}}$ , equatorial deformation radius  $L_D$ , and the Rhines' scale  $L_\beta$  are from general circulation models. From Kataria et al. (2016), Table 1.

Planet	$R_p$ ( $R_J$ )	$T_{\text{orb}} = T_{\text{rot}}$ (Earth days)	$\Omega$ ( $10^{-5} \text{ s}^{-1}$ )	$g$ ( $\text{ms}^{-2}$ )	$T_{\text{eq}}$ (K)	$F_\star$ ( $\text{Wm}^{-2}$ )	$H$ (km)	$Ro$	$N_{\text{jets}}$	$L_D$ ( $\times 10^7 \text{ m}$ )	$L_\beta$ (km)
HAT-P-1 b	1.32	4.46	1.631	7.46	1322	7.016 e5	670	1.32	1.17	8.0	24.8
HAT-P-12 b	0.96	3.21	2.263	5.62	963	1.917 e5	648	0.82	1.28	5.4	16.7
HD 189733 b	1.14	2.22	3.279	21.40	1201	4.632 e5	212	0.67	1.59	5.1	16.4
HD 209458 b	1.36	3.52	2.066	9.35	1448	1.001 e6	585	1.26	1.31	7.4	24.6
WASP-6 b	1.22	3.36	2.164	8.71	1145	3.452 e5	497	0.89	1.26	7.2	19.6
WASP-17 b	1.89	3.73	1.950	3.57	1738	2.140 e6	1840	1.09	1.43	9.4	26.9
WASP-19 b	1.41	0.79	9.217	14.21	2050	4.392 e6	545	0.32	2.59	3.9	12.5
WASP-31 b	1.55	3.40	2.139	4.56	1575	1.399 e6	1305	1.06	1.40	7.9	24.0
WASP-39 b	1.27	4.06	1.793	4.07	1117	3.548 e5	1037	0.92	1.35	6.5	20.3

cause of weaker spectral signatures. Kataria et al. (2016) derived the atmospheric properties of these systems with general circulation models, and their summary results are shown in Table 11.7.

In the mid-infrared, features are typically broader and more intense than in the visible. As predicted from theoretical models, spectra appear to be dominated by  $\text{H}_2\text{O}$  vapour, as seen in HD 209458 (e.g. Barman, 2007; Swain et al., 2009b; Beaulieu et al., 2010b), and HD 189733 (e.g. Tinetti et al., 2007b; Barman, 2008; Charbonneau et al., 2008; Grillmair et al., 2008).

$\text{CH}_4$  has also been detected in HD 189733 b (Swain et al., 2008b; Waldmann et al., 2012), and HD 209458 (Swain et al., 2009b). Swain et al. (2014) noted that, in the case of the claimed  $\text{CH}_4$  detection for HD 189733 b *‘with what is probably the best analysed exoplanet spectroscopy data set to date, different teams, using different methods, have claimed evidence both contradicting and supporting the original findings’*, but concluded that the claimed detection stands.

Warm Neptunes are also expected to be  $\text{CH}_4$ -rich, although observational constraints are presently limited. The principal targets have been GJ 436 b (e.g. Beaulieu et al., 2011; Knutson et al., 2011; Line et al., 2011), and GJ 3470 b (Fukui et al., 2013).

CO is more problematic, even with space facilities, where the available spectral resolution is insufficient to distinguish it from  $\text{CH}_4$  or  $\text{CO}_2$ . The method developed by Snellen et al. (2010a) using VLT-CRILES (§2.5.4), gave the first robust detection of CO in the atmospheres of HD 209458 b and HD 189733 b (de Kok et al., 2013), and can also be used for non-transiting planets, as shown for  $\tau$  Boo b (Brogi et al., 2012b).

**GJ 1214** At lower masses, the warm planet GJ 1214 b ( $6M_\oplus$ ,  $0.02M_J$ ,  $P = 1.5 \text{ d}$ ,  $M_\star = 0.2M_\odot$ ,  $V = 15$ ) was the first ‘super-Earth’ to be examined spectroscopically, with VLT-FORS2 (Bean et al., 2010a), followed by various other space and ground observations (e.g. Bean et al., 2011; Croll et al., 2011a; Crossfield et al., 2011; Désert

et al., 2011a; Berta et al., 2012a; de Mooij et al., 2012, 2013a; Colón & Gaidos, 2013; Fraine et al., 2013; Kreidberg et al., 2014b; Wilson et al., 2014a).

Various theoretical and modeling studies have been made (Rogers & Seager, 2010b; Menou, 2012a; Miller-Ricci Kempton et al., 2012; Howe & Burrows, 2012; Valencia et al., 2013; Morley et al., 2013; Barstow et al., 2013; Kataria et al., 2014; Charnay et al., 2015a,b).

The featureless spectrum has been interpreted as either due to an atmosphere dominated by relatively heavy molecules, such as  $\text{H}_2\text{O}$  (e.g. a 100%  $\text{H}_2\text{O}$ -vapour composition), or it could contain high-altitude clouds that obscure its lower layers. HST transit spectra, considered sufficiently precise to detect absorption features from a high mean-molecular-mass atmosphere, have suggested that the planet’s atmosphere must contain clouds (Kreidberg et al., 2014b).

**Other results from eclipse spectra** Table 11.8 lists the planets with published photometric eclipse measurements in at least two thermal wavelengths ( $\lambda > 1 \mu\text{m}$ ), updated to 31 December 2017 from the review by Hansen et al. (2014). In most cases, only a single secondary eclipse has been measured at each wavelength. Table 11.8 includes their orbital periods (illustrating that they are all close orbiting), their masses (showing that only one, GJ 436 b, is other than a hot Jupiter), and their  $V$  magnitudes (showing that the brightest host stars make the favoured targets).

From a combination of near- and mid-infrared eclipse spectra acquired from space and ground, various absorption features have been claimed, and some of which have been contested. Spectral features due to  $\text{H}_2\text{O}$ ,  $\text{CH}_4$ , CO and  $\text{CO}_2$  appear to explain the most prominent features present in the hot-Jupiters observed to date. This can be seen by an inspection of the results for two of the best-observed systems, HD 189733 b (Table 11.6.2) and HD 209458 b (Table 11.6.2). The challenges in modeling can be appreciated by an inspection of the compilation of results for these two sys-

Table 11.8: Exoplanets with eclipse photometry in at least two thermal wavelengths ( $\lambda > 1 \mu\text{m}$ ), updated from Hansen et al. (2014, Table 1) as of 31 December 2017. In most cases, only a single secondary eclipse has been measured at each wavelength; those with an asterisk are based on multiple eclipses. Detailed bibliographies are given in Appendix D.

Planet (all 'b')	$P$ (d)	$M_p$ ( $M_J$ )	$V$	Wavelengths ( $\mu\text{m}$ )
CoRoT-1	1.5	1.0	13.6	1.6,2.1,3.6,4.5
CoRoT-2	1.7	3.5	12.6	2.1,3.6,4.5,8
GJ 436	2.6	0.07	10.7	3.6,4.5,5.8,8*,16,24
HAT-P-1	4.4	0.5	10.3	3.6,4.5,5.8,8
HAT-P-2	5.6	9.1	8.7	3.6,4.5,5.8,8
HAT-P-3	2.9	0.6	11.5	3.6,4.5
HAT-P-4	3.1	0.6	11.1	3.6,4.5
HAT-P-6	3.8	1.1	10.4	3.6,4.5
HAT-P-7	2.2	1.7	10.5	3.6,4.5,5.8,8
HAT-P-8	3.1	1.5	10.3	3.6,4.5
HAT-P-12	3.2	0.2	12.8	3.6,4.5
HAT-P-13	2.9	0.8	10.6	3.6,4.5
HAT-P-19	4.0	0.3	12.9	3.6,4.5
HAT-P-23	1.2	2.1	11.9	2.1,3.6,4.5
HAT-P-32	2.2	0.8	11.2	1.6,2.1,3.6,4.5
HD 149026	2.9	0.4	8.2	3.6,4.5,5.8,8*
HD 189733	2.2	1.2	7.7	2.1,3.6*,4.5*,5.8,8*,16,24
HD 209458	3.5	0.7	7.6	2.1,3.6,4.5*,5.8,8,24*
KELT-1	1.2	27.2	10.7	3.6,4.5
Kepler-5	3.5	2.1	13.4	3.6,4.5
Kepler-6	3.2	0.7	13.3	3.6,4.5
Kepler-12	4.4	0.4	13.8	3.6,4.5
Kepler-13A	1.8	9.3	10.0	2.1,3.6,4.5
Kepler-17	1.5	2.4	14.1	3.6,4.5
TrES-1	3.0	0.7	11.8	3.6,4.5,8
TrES-2	2.5	1.2	11.4	2.1,3.6,4.5,5.8,8
TrES-3	1.3	1.9	12.4	1.25,2.1,3.6,4.5,5.8,8
TrES-4	3.6	0.5	11.6	3.6,4.5,5.8,8
WASP-1	2.5	0.8	11.8	3.6,4.5,5.8,8
WASP-2	2.2	0.9	11.9	3.6,4.5,5.8,8
WASP-3	1.8	2.9	10.5	3.6,4.5,8
WASP-4	1.3	1.2	12.5	2.1,3.6,4.5
WASP-5	1.6	1.6	12.3	1.25*,1.6*,2.1*,3.6,4.5
WASP-6	3.4	0.5	11.9	3.6,4.5,8
WASP-8	8.2	2.2	9.8	3.6,4.5,8
WASP-10	3.1	3.2	12.7	2.1,3.6,4.5
WASP-12	1.1	1.5	11.7	1.25,1.6,2.1,3.6*,4.5*,5.8,8
WASP-14	2.2	7.3	9.8	3.6,4.5
WASP-17	3.7	0.5	11.6	4.5,8
WASP-18	0.9	10.4	9.3	3.6*,4.5*,5.8,8
WASP-19	0.8	1.1	12.6	1.6,3.6,4.5,5.8,8
WASP-24	2.9	0.9	11.2	3.6,4.5
WASP-26	2.8	1.0	11.3	3.6,4.5
WASP-33	1.2	4.1	8.1	2.1,3.6,4.5
WASP-39	4.0	0.3	12.1	3.6,4.5
WASP-43	0.8	1.8	12.4	3.6,4.5
WASP-48	2.1	0.9	11.8	1.6,2.1,3.6,4.5
WASP-67	4.6	0.4	12.5	3.6,4.5
WASP-80	3.1	0.5	11.9	3.6,4.5
XO-1	3.9	0.9	11.2	3.6,4.5,5.8,8
XO-2	2.6	0.6	11.1	3.6,4.5,5.8,8
XO-3	3.2	11.8	9.8	3.6,4.5*,5.8,8
XO-4	4.1	1.8	10.7	3.6,4.5

tems as observed by multiple groups and with different instruments (see Tinetti et al., 2013, their Figures 7a and 7b). While, at least for these two systems, the different radiative-transfer models and spectral retrieval schemes indicate the same atmospheric composition, there is no agreement yet on the abundances found.

The emission spectra of a number of planets are found to be featureless, e.g. TrES-2 (O'Donovan et al., 2010), TrES-3 (Fressin et al., 2010), WASP-12 b (Crossfield et al., 2012a) and WASP-18 b (Nymeyer et al., 2011). They are interpreted as indicative of an isothermal atmosphere, or for cloud decks in the upper atmospheres.

**Status of transit and eclipse spectroscopy** Some of the challenges in transit and eclipse spectroscopy are set out in Section 11.6. These are related both to the inherent complexity of exoplanet atmospheres (in terms of chemistry, dynamics, structural profiles, unknown opacities, the presence of clouds and hazes, and their potential sensitivity to trace chemical species), as well as the limited broad-band photometry available to probe them. Accordingly, various reviewers have also urged some caution in over-interpreting the data (e.g. Tesseney et al., 2013; Tinetti et al., 2013; Bailey, 2014; Burrows, 2014b,a; Hansen et al., 2014; Deming & Seager, 2017).

Some 'over-interpretation' is presumably responsible for at least some of the different spectral features identified by different observers. As argued by Burrows (2014b): '*with a few photometric points, one cannot simultaneously determine with any confidence, or credibly incorporate into the fitting procedures, chemical and elemental abundances, wind dynamics, longitudinal heat redistribution, thermal profiles, albedos, the potential influence of hazes and clouds, non-equilibrium chemistry and photochemistry, and magnetic fields*'.

A statistical assessment of the various eclipse data compiled from Spitzer observations has helped to quantify these concerns. Hansen et al. (2014, see, e.g., his figure 1) concluded that just seven planets observed to date justify a 'full spectral retrieval': CoRoT-2 b, GJ 436 b, HAT-P-8 b, HD 189733 b, WASP-1 b, WASP-8 b, and XO-3 b. Of these, CoRoT-2 b exhibits the most featured broad-band emission spectrum although there may also be other contributory effects (Deming et al., 2011a; Madhusudhan, 2012).

Burrows (2014b) has suggested that the past two decades '*have been but a training period for a new generation of exoplanet scientists, forged by trial and error, and educated in the new questions posed by exoplanets*'. At the same time, he stresses its exciting future with the availability of high-quality spectra across a broad range of wavelengths from the optical to the mid-infrared.

### 11.6.3 Atmospheric insights from phase curves

The general treatment of orbital phase curves, as a result of light reflected by an orbiting planet (or planets), is considered in Section 6.15. Although there is some overlap in these topics, this section details specific observational properties of orbital phase curves related to conditions in the planet's atmosphere. Inferences and conclusions draw on studies of the phase- and wavelength-

dependent emission of hot Jupiters simulated with various atmospheric models, including dependence on eccentricity, orbit inclination, and obliquity (e.g. Barman et al., 2005; Sudarsky et al., 2005; Fortney et al., 2006a; Showman et al., 2009; Burrows et al., 2010; Cowan & Agol, 2011a; Kane & Gelino, 2011b; Selsis et al., 2011; Cowan et al., 2012c, 2013; Schwartz et al., 2016; Cowan et al., 2017; Haggard & Cowan, 2018), as well as on atmospheric ‘general circulation models’ more widely (§11.4.2), as used in the interpretation of transmission and emission spectroscopy.

**Eastward shifts and superrotation** Hot Jupiters exhibit day–night temperature contrasts of  $\sim 1000$  K, and the planet’s temperature, and hence brightness, accordingly vary as a function of local stellar time. This inhomogeneous intensity is most simply modeled with three parameters (Cowan et al., 2012b): the orbit-averaged planet/star flux ratio,  $\langle F_p/F_\star \rangle$ , the semi-amplitude of thermal phase variations,  $A_{\text{therm}}$ , and the offset of the phase peak from superior conjunction,  $\alpha_{\text{max}}$ , where  $\alpha_{\text{max}} < 0$  corresponds to a peak prior to superior conjunction, i.e. to an eastward-advected hot spot (i.e. to superrotating winds).

In the limit of instant re-radiation, the light curve morphology is entirely dictated by the planet’s eccentricity and argument of pericentre: the light curve maximum leads or trails the eclipse depending on whether the planet is receding from or approaching the star at superior conjunction (Cowan & Agol, 2011a). For a planet with non-zero radiative time scales, the phase peak occurs early for superrotating winds.

Observations of the first complete orbit light curve, for CoRoT-1 (Snellen et al., 2009a), were found to be well reproduced by a day-side hemisphere of uniform surface brightness with a ratio of planet to stellar flux (from the transit depth and the phase variation) of  $1.26 \times 10^{-4}$ , and a night-side ratio (from the secondary eclipse depth of 0.016% and the phase variation) of  $< 3 \times 10^{-5}$ , consistent with the night-side hemisphere being entirely black. A similar, complete, phase curve was reported for HAT-P-7 b as observed by Kepler (Borucki et al., 2009).

As the full orbital phase curves of more transiting planets have been measured, at both optical and infrared wavelengths, a displacement between the substellar point and the brightest region on the planet surface has been detected for some. Short-period planets generally (but see below) exhibit *eastward* ‘hot spot offsets’ whereby the hottest region on the planet is shifted east of the substellar point. As detailed in Section 11.4.2, such an eastward-shifted hot spot, signifying the advection of gas by an equatorial (‘westerly’) super-rotating jet (§11.4.2), is a recurring prediction of hot Jupiter 3d atmospheric circulation models.

In the case of HD 189733 b (§11.6.2), Knutson et al. (2007a) measured a small thermal gradient between

day-side and night-side using Spitzer–IRAC at  $8 \mu\text{m}$ , and showed an offset of the hottest point of the disk relative to the substellar point, suggesting an energy transport from the stellar side to the anti-stellar side. Further analyses (de Wit et al., 2012; Majeau et al., 2012) derived 2d thermal intensity maps of the planet using Spitzer–IRAC at  $8 \mu\text{m}$ . Further observations have since been made at other infrared wavelengths (Cowan et al., 2007; Knutson et al., 2009c, 2012)

Full-orbit Spitzer phase curves at  $4.5 \mu\text{m}$  (and for some, at other wavelengths) have been reported for 10 exoplanets on *circular* orbits. The first nine all exhibit phase offsets consistent with such an *eastward* hot spot offset (or no significant offset): WASP-12 b (Cowan et al., 2012b); HD 189733 b (Knutson et al., 2012); WASP-18 b (Maxted et al., 2013b); HD 209458 b (Zellem et al., 2014b); WASP-14 b (Wong et al., 2015); WASP-19 b (Wong et al., 2016); HAT-P-7 b (Wong et al., 2016); 55 Cnc e (Demory et al., 2016b); and WASP-43 b (Blecic et al., 2014; Stevenson et al., 2017).

Eastward shifts were also found in the reflection signal in the optical (Kepler) phase curves of Kepler-76 b (Faigler et al., 2013), and HAT-P-7, Kepler-13 and Kepler-76 (Faigler & Mazeh, 2015).

Other phase curve observations that have revealed day–night temperature contrasts and hot spot offsets relative to the substellar point include HD 149026 from Spitzer–IRAC at  $8 \mu\text{m}$  (Knutson et al., 2009b); and the eccentric HAT-P-2 from Spitzer–IRAC at 3.6, 4.5, 5.8, and  $8.0 \mu\text{m}$  (Lewis et al., 2013).

**Westward shifts and inhomogeneous clouds** Esteves et al. (2013) found that the optical phase curves of Kepler-13 and HAT-P-7 showed periodicity at three times the orbit frequency which they attributed to the effects of rotation and spin–orbit misalignment (§6.14.3).

With similar higher harmonics subsequently identified in 13 KOI candidates (Armstrong & Rein, 2015), including Kepler-252, the most probable origin was considered to be non-isotropic reflection or thermal emission from the planet’s surface, consistent with the idea of inhomogeneous cloud cover. While enhancing the prospects of atmospheric characterisation, such an origin would also affect estimates of planet albedos, beaming mass estimates, and ellipsoidal variations.

Again at *optical* wavelengths, some hot Jupiters have been found to show a *westward* phase shift between the brightest region on the planet surface and the substellar point, amongst them Kepler-7 b, with an offset of  $41 \pm 12^\circ$  (Demory et al., 2013a; Hu et al., 2015a), Kepler-12 b and Kepler-41 b (Shporer & Hu, 2015).

Conflicting with the predictions of hot Jupiter circulation models, these westward shifts have also been attributed to reflected optical light from inhomogeneous reflective clouds on the west side of the substellar point (e.g. Demory et al., 2013a; Shporer & Hu, 2015; Webber

et al., 2015; García Muñoz & Cabrera, 2018).

From 4 years of Kepler data of HAT-P-7, Armstrong et al. (2016a) reported temporal atmospheric variability, finding that the peak brightness repeatedly shifts from one side of the planet's substellar point to the other on a time scale of tens to hundreds of days. They attributed this to a changing balance of thermal emission and reflected flux from the planet's day-side, in turn attributed to variable cloud cover.

Asymmetric transit light curves attributable to inhomogeneous cloud cover (§6.14.8) have been (unsuccessfully) searched for in HAT-P-7, HD 209458, and Kepler-7 (von Paris et al., 2016a). Counter arguments to the idea of inhomogeneous cloud cover, and suggestions of artefacts and tides, are given by Cowan et al. (2017).

**CoRoT-2** In contrast to the first nine hot Jupiters showing eastward-shifted hot spots at  $4.5 \mu\text{m}$ , indicative of atmospheric superrotation, the tenth, CoRoT-2 b, shows a *westward* hotspot offset of  $23 \pm 4^\circ$  (Dang et al., 2018). Not adhering to the predictions of relevant atmospheric circulation models, their explanations for this westward offset include westward winds due to non-synchronous rotation, viz. non-tidal locking (Rauscher & Kempton, 2014); magnetic effects (Rogers & Komacek, 2014; Rogers, 2017); or partial cloud coverage that obscures the emergent flux from the planet's eastern hemisphere (Demory et al., 2013a; Parmentier et al., 2016; Lee et al., 2016; Roman & Rauscher, 2017).

At the same time, non-synchronous rotation and magnetic effects may also explain the anomalously large radius of CoRoT-2 b (Guillot & Havel, 2011; Rogers & Komacek, 2014), while partial cloud coverage could explain the planet's featureless day-side emission spectrum (Moses et al., 2013c; Wilkins et al., 2014).

**Non-transiting planets** Phase-curve measurements, in emitted and/or reflected light, can also be obtained for suitably inclined, close-in, *non-transiting* planets, as first performed at  $24 \mu\text{m}$  for  $\nu$  And b (Harrington et al., 2006; Crossfield et al., 2010). This is considered further in Section 6.15.

**Effect of obliquity** Kawahara (2016) modeled the frequency modulation of apparent diurnal periodicity due to the combined effects of obliquity and orbit inclination, assuming a static albedo. The shape of the instantaneous frequency response can in principle distinguish between prograde, retrograde, and pole-on spin rotations. Associated 3d atmospheric circulation models, emphasising the observable signatures of obliquity for (non-tidally aligned) warm Jupiters, and their detection prospects with JWST, are given by Rauscher (2017).

Reconstruction of the planet's spin axis from time-resolved photometry is detailed by Schwartz et al. (2016), with the finding that east-west albedo contrast is more useful for constraining obliquity than north-south contrast.

**Prospects for terrestrial planets** For terrestrial mass planets, Koll & Abbot (2015) used general circulation models (box, page 593) to establish phase curve features most sensitive to atmospheric parameters, showed how such measurements can be combined with transit or emission spectroscopy to yield

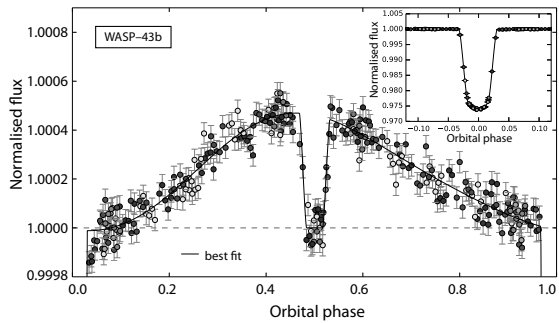


Figure 11.34: *HST* phase curve of WASP-43 b spanning three planet rotations (grey scale points are data from different visits). The phase curve depicts steadily increasing and decreasing flux which originates from different longitudes of the tidally-locked planet as it orbits. Light from the planet is blocked near orbital phase 0.5 where it is eclipsed by the host star. The model phase curve maximum occurs  $40 \pm 3$  min prior to the secondary eclipse midpoint, corresponding to a  $12.3 \pm 1.0^\circ$  eastward shift of the substellar point. The model phase curve minimum occurs  $34 \pm 5$  min after the primary transit midpoint, or  $10.6 \pm 1.4^\circ$  west of the anti-stellar point. As a result, maximum planetary emission occurs  $0.436 \pm 0.005$  orbits after the observed minimum (for depths probed by these observations) and the shape of the phase curve is asymmetric. The inset is the white light curve primary transit. From Stevenson et al. (2014d, Figure 1), reprinted with permission from AAAS.

constraints on surface pressure and atmospheric mass, and concluded that a single broad-band phase curve, measured over half an orbit with JWST, could meaningfully constrain the atmospheric mass of a nearby super-Earth. Gómez-Leal et al. (2016) used LMDZ to simulate the climate of a synthetic Earth and three 'quasi-Earth' configurations: a slowly rotating Earth, an ocean-covered Earth and its snowball counterpart. Improved characterisation of phase curves by means of stellar coronagraphy was considered by Frolov et al. (2015), issues of parameter degeneracy by Fujii et al. (2017a), and prospects for determining exotopography by McTier & Kipping (2018).

**Algorithmic implementation** Analytic reflected light curves for spherical harmonic albedo maps are given for a synchronously rotating planet on an edge-on orbit by Cowan et al. (2013). Haggard & Cowan (2018) give analytic reflected light curves for the general case of a planet on an inclined orbit, with arbitrary spin period and non-zero obliquity, and for two different albedo basis maps: bright points ( $\delta$ -maps), and spherical harmonics ( $Y_l^m$ -maps). The code is made available as EARL, Exoplanet Analytic Reflected Light curves.

**Bond albedo and heat redistribution** Estimates of Bond albedo,  $A_B$ , and heat redistribution efficiency,  $f$ , for 24 planets with at least one published secondary eclipse (Cowan & Agol, 2011b) rejected the null hypothesis of a single  $A_B$  and  $f$  (Equation 6.158), finding that low albedos ( $A_B < 0.35$ ) are favoured, an independent confirmation of the low albedos inferred from the non-detections of reflected light. Outliers in  $f$  are the two eccentric planets, GJ 436 and HD 80606.

The full *HST* phase curve of the highly-irradiated WASP-43 b, spanning three planet rotations (Stevenson

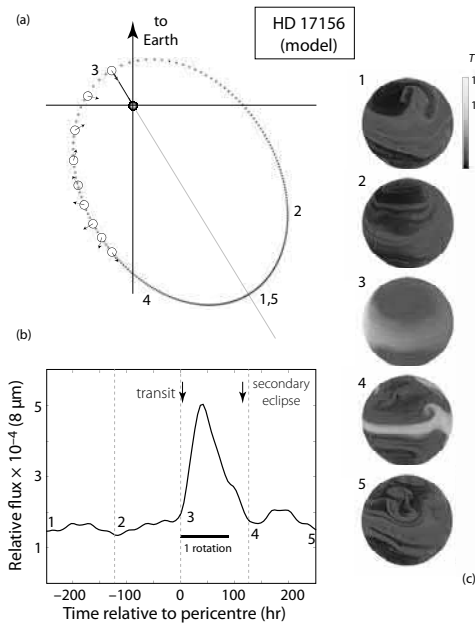


Figure 11.35: Model weather patterns for HD 17156 b. (a) orbit geometry: dots show the planet position at 2.4-hr intervals over the 21.2 d orbit, with its location at time intervals of one quarter of an orbit indicated (1–5). Small circles indicate the 91.3 h spin frequency of the planet, which is expected to be in pseudo-synchronous rotation; (b) predicted  $8\ \mu\text{m}$  planet light curve over the orbit; (c) predicted planet temperature maps at locations 1–5, as viewed from Earth. From Irwin et al. (2008a, Figure 4), by permission of IOP Publishing/AAS.

et al., 2014d) is shown in Figure 11.34. From a reconstruction of the planet's atmospheric thermal structure, they derived a Bond albedo of  $0.18^{+0.07}_{-0.12}$ , and found large day–night temperature variations at all measured altitudes, a monotonically decreasing temperature with pressure at all longitudes, and an altitude dependence in the hot-spot offset relative to the substellar point.

**Long-period high-eccentricity orbits** Further complexity in radiative models occurs for highly eccentric orbits (e.g. HD 17156 and HD 80606), where the effects of planet (pseudo-synchronous) rotation have been described (e.g. Irwin et al., 2008a; Iro & Deming, 2010).

As an example of the weather patterns that may be observable in the future, Irwin et al. (2008a) derived hydrodynamical-model temperature maps for the highly eccentric ( $P = 21.2\ \text{d}$ ,  $e = 0.67$ ) transiting planet HD 17156 b. The planet is predicted to be in a *pseudo-synchronous orbit*, in which its spin is roughly synchronous with the orbit during the interval around pericentre (Hut, 1981), with an estimated  $P_{\text{spin}} \sim 91.3\ \text{h}$ . The planet's high eccentricity leads to a 25-fold variation in stellar flux over the orbit, resulting in complex weather patterns over its photosphere (Figure 11.35).

For the eccentric long-period hot Jupiter HD 80606 b

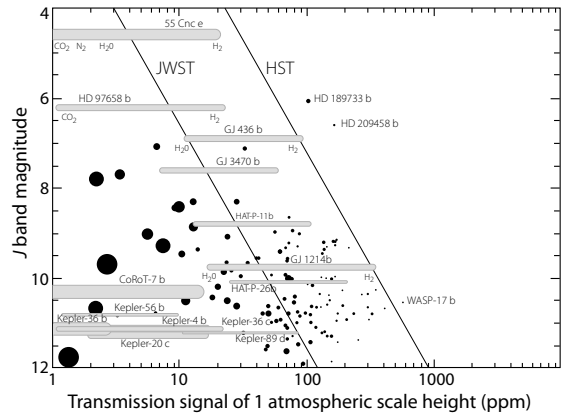


Figure 11.36: Detectability of planet atmospheres with JWST and HST (at  $3\sigma$ ), for super-Earths/Neptunes with  $\sigma(M_p)/M_p < 0.2$ . The signal of one atmospheric scale height seen in transmission during transit is calculated as  $2 \times 10^6 (\Delta F/F)(H/R_p)$ , where  $\Delta F/F$  is the transit depth and  $H$  is the scale height (Equation 6.153). Circle size (and bar thickness) is proportional to  $\rho_p$ . For giant planets, the atmosphere is assumed to be  $\text{H}_2 + \text{He}$ . For lower-mass planets, the atmospheric composition is unknown, and the bar's extent represents all possible values. From Pepe et al. (2014a, Figure 2), by permission from Nature/Springer/Macmillan Ltd, ©2014.

( $P = 111\ \text{d}$ ,  $e = 0.93$ ), de Wit et al. (2016a) used multi-day multi-channel Spitzer photometry to resolve the degeneracy between the atmosphere's radiative and dynamical time scales, and constrain its global thermal response. The atmospheric layers probed heat rapidly ( $\sim 4\ \text{h}$ ) from  $\lesssim 500\ \text{K}$  to  $\sim 1400\ \text{K}$  as they absorb 20% of the incident stellar flux during pericentre passage, while the planet's rotation period  $P_{\text{rot}} = 93^{+85}_{-35}\ \text{h}$  exceeds the predicted pseudo-synchronous period of 40 h.

Eccentric orbits with periods significantly longer than their radiative time constant should exhibit *ringing*, in which the hot spot generated at pericentre rotates in and out of view, allowing measurement of the wind speed, given by the ringing frequency, and the radiative time constant, by the damping (Cowan & Agol, 2011a).

#### 11.6.4 Future prospects

The near-term future of atmospheric characterisation, and for a wider variety of environments, should be advanced significantly by JWST (§6.8.3, Figure 11.36). High sensitivity and broad wavelength coverage will allow high S/N transit measurements. Its spectroscopy will probe atmospheres to determine atomic and molecular compositions, vertical and horizontal structures, and dynamical evolution (Seager et al., 2009; Belu et al., 2011; Beichman et al., 2014a; Crossfield & Kreidberg, 2017).

Simulations suggest that, in the absence of clouds or hazes, absorption features for an Earth-like or super-Earth planet could be detected with 200 hr of JWST in-transit observations (Deming et al., 2009; Shabram et al.,

2011; Misra et al., 2014a), or with >20 hr of E-ELT in-transit observations (Pallé et al., 2011; Hedelt et al., 2013; Rodler & López-Morales, 2014).

Beyond JWST, facilities will include the extremely-large telescopes (ELTs/GSMTs), perhaps dedicated space missions (as envisaged with EchO; \$6.8.4), and a possible coronagraph on WFIRST-AFTA (\$5.9.5). In the further future, a major space mission dedicated to atmospheric characterisation, as previously envisaged with TPF and Darwin (\$7.7.3), may be possible.

Currently, giant planets and Neptunes pose the most realistic targets, and more bright nearby candidates are expected from TESS and PLATO (\$6.8.1). In addition, terrestrial planets, ten times smaller in radius and one hundred times smaller in mass, and the possibility of discerning signatures of life are major goals, with the spectra of terrestrial planet atmospheres around nearby M dwarf stars possibly within reach.

### 11.7 Habitability

The discovery and characterisation of exoplanets has progressed to the point where terrestrial planets are being discovered in reasonable numbers, some of which lie at star-planet separations which place them within their star's 'habitable zone'. There is now good reason to believe that such planets exist in very large numbers.

Improvements in spectroscopy, from ground or space, and improved atmospheric models, will also guide the search for planets which are both habitable, but also show specific atmospheric features more conducive to life. Search strategies will be dictated by observational feasibility (e.g. Schneider, 1994b; Mariotti et al., 1997; Léger, 1999; Schneider et al., 2010), and assisted by an improved understanding of the conditions required for development of life on Earth (e.g. Gogarten, 1998; Des Marais, 1998; McKay, 1998; Javaux & Dehant, 2010).

**Astrobiology** The new discipline of *astrobiology*, refers to the study of the origin, evolution, distribution, and future of life in the Universe. It encompasses the search for habitable environments in the solar system and beyond, and for biospheres that might be very different from Earth's. It is a cross-disciplinary effort, with knowledge from astronomy, biology, chemistry, geography, geology, physics, and planetary science (Chyba & Hand, 2005; Impey, 2010; Dick, 2012). According to Briot (2012), the term was first used by A.J. Sternfeld in 1935. Today, it largely supersedes the term 'exobiology' which relates to the search for life beyond Earth.

The discovery of exoplanets has catalysed many new astrobiology initiatives (e.g. Cowan et al., 1999; Des Marais et al., 2003, 2008), along with many conferences related to the search for life (e.g. Cosmovici et al., 1997; Des Marais, 1997; Woodward et al., 1998; Apai & Gabor, 2014). Advances are informing the philosophical debate

**NASA, ESA and other astrobiology roadmaps:** NASA's astrobiology roadmap addresses three basic questions: how does life begin and evolve, does life exist elsewhere in the Universe, and what is the future of life on Earth and beyond? The key domains of investigation are summarised by Des Marais et al. (2008) as:

(1) understand the nature and distribution of habitable environments in the Universe. Determine the potential for habitable planets, and characterise those observable;

(2) determine past or present habitable environments, prebiotic chemistry, and signs of life elsewhere in our solar system. Determine the history of any environments having liquid water, chemical ingredients, and energy sources;

(3) understand how life emerges from cosmic and planetary precursors. Perform observational, experimental, and theoretical investigations to understand the general physical and chemical principles underlying the origins of life;

(4) understand how life on Earth and its planetary environment have co-evolved through geological time. Investigate the evolving relationships between Earth and its biota by integrating evidence from the geosciences and biosciences that shows how life evolved, responded to environmental change, and modified environmental conditions on a planetary scale;

(5) understand the evolutionary mechanisms and environmental limits of life. Determine the molecular, genetic, and biochemical mechanisms that control and limit evolution, metabolic diversity, and acclimatisation of life;

(6) understand the principles that will shape the future of life, on Earth and beyond. Elucidate the drivers and effects of microbial ecosystem change as a basis for forecasting future changes on time scales ranging from decades to millions of years, and explore the potential for microbial life to survive and evolve in environments beyond Earth;

(7) determine how to recognise signatures of life on other worlds and on early Earth. Identify biosignatures that can reveal and characterise past or present life in ancient samples from Earth, extraterrestrial samples measured *in situ* or returned to Earth, and remotely measured planetary atmospheres and surfaces. Identify biosignatures of distant technologies.

An early ESA astrobiology roadmap is described by Fridlund et al. (2010a). A more recent European astrobiology roadmap is detailed by Horneck et al. (2016). A proposed atmosphere and habitability roadmap for China is given by Tian et al. (2017a).

surrounding the question of life beyond Earth that has been ongoing for centuries (Crowe, 1986; Dick, 1996).

Amongst these, NASA's 'Nexus for Exoplanet System Science' (NExSS) initiative, started in 2015, is a virtual institute of 17 teams, led by the Ames Research Center, the NASA Exoplanet Science Institute, and the Goddard Institute for Space Studies, designed to foster interdisciplinary collaboration in the search for life on exoplanets (Fortney et al., 2016b).

Taking NASA's 2008 'astrobiology roadmap' (Des Marais et al., 2008) as an outline of the objectives considered under the umbrella term of astrobiology (box, page 618), topics considered here focus only on the first (*viz.*, the nature and distribution of habitable environ-

ments in the Universe), and a subset of the last (viz., identifying biosignatures that can reveal and characterise past or present life in remotely measured planetary atmospheres and surfaces).

Various books and reviews provide an evolving introduction to the wider panorama of astrobiology, habitability, and the search for life (e.g. Grady, 2001; Gilmour & Sephton, 2004; Lunine, 2005; Howard, 2005; Billings et al., 2006; Horneck & Rettberg, 2007; Scharf, 2009; Lazcano & Hand, 2012; Cockell, 2015; Domagal-Goldman et al., 2016; Cottin et al., 2017; Kaltenegger, 2017).

### 11.7.1 Habitable zone

**Early ideas** Early concepts of a ‘habitable zone’ date back to Richard Bentley (1662–1742), who ‘*praised God’s wisdom in placing our planet at just such a distance from the sun that we are neither too cold nor too hot*’ (quoted by Crowe, 1986, p23), and to William Whewell (1858), who referred to the ‘*temperate zone of the solar system*’ (quoted by Heller & Armstrong, 2014).

Huang (1959) presented a general discussion of the ‘habitable zone of a star’, and considered time scales of stellar evolution, dynamical constraints in stellar multiple systems, and the stellar Galactic orbit. A broader consideration of habitability was given by Dole (1964).

Current assessment of the suitability of a planet for supporting life is largely based on the knowledge of life on Earth. With the general consensus among biologists that carbon-based life requires water for its self-sustaining chemical reactions (Owen, 1980), the search for habitable planets has focused on identifying environments in which liquid water is stable, preferably over billions of years. The presence of liquid water in turn implies that the atmospheric pressure and ambient temperature will be in ranges that promote a rich variety of organic reactions although, even on Earth, not all water is inhabited (Jones & Lineweaver, 2010).

A *life supporting zone* extends the concept of a zone conducive to H<sub>2</sub>O-based life to other solvents (Neubauer et al., 2012; Ludwig et al., 2016).

**Circumstellar habitable zone** As a result, the (circumstellar) *habitable zone* is loosely defined by the range of star–planet distances where liquid water can exist on its surface (Huang, 1959, 1960; Dole, 1964; Hart, 1979; Kasting et al., 1993; Kasting, 1996; Williams et al., 1997; Kasting, 2008; Lammer et al., 2009a; Dobos et al., 2013). Primarily controlled by the star–planet separation, it is also affected by the planet’s atmospheric properties including composition and circulation, tidal heating, and orbital effects including eccentricity and planet rotation.

The habitable zone will be extended outwards by a variety of other effects, including other sources of atmospheric irradiation, including stellar X-ray heating due to photoionisation and Compton scattering (Cecchi-Pestellini et al., 2006), by additional internal heating

**Runaway greenhouse state:** Planetary atmospheres settle into a thermal equilibrium state where the (outgoing) thermal emission balances the heating due to the absorption of sunlight. The resulting climate is stabilised by the fact that a temperature increase results in enhanced cooling through thermal emission. When a condensable greenhouse gas is present, such as H<sub>2</sub>O on Earth, this stabilising feedback is modified: evaporation, and thus H<sub>2</sub>O-vapour greenhouse effect, increases with temperature, reducing the cooling. Under present Earth conditions, greenhouse feedback is both strong enough to maintain surface temperatures, yet weak enough for the climate to remain stable (Leconte et al., 2013b).

As solar heating becomes stronger, H<sub>2</sub>O-vapour can make the atmosphere optically thick at all thermal wavelengths. The thermally-emitted flux then originates only from the upper troposphere, and reaches some maximum value,  $F_{\text{rg}}$ , independent of the surface temperature (e.g. Nakajima et al., 1992).  $F_{\text{rg}}$  has been variously estimated as 305 W m<sup>-2</sup> (Abe & Matsui, 1988), 309 W m<sup>-2</sup> (Kasting, 1988), 291 W m<sup>-2</sup> (Kopparapu et al., 2013), and 301 W m<sup>-2</sup> (Heller & Armstrong, 2014). If the planet absorbs more than this critical flux, thermal equilibrium can only be restored by vaporising all of the water, and achieving high surface temperatures at which the surface starts to radiate at visible wavelengths. The condition in which the ocean cannot exist in equilibrium is referred to as the *runaway greenhouse state*.

Equating the energy absorbed by Earth (in terms of the solar constant,  $S = 1370 \text{ W m}^{-2}$  and Earth’s albedo,  $A$ ) to that emitted by Earth (in terms of its blackbody temperature,  $T_{\oplus}$ ), yields  $\sigma T_{\oplus}^4 = (S/4)(1 - A) \text{ W m}^{-2}$ , and hence a *solar flux*  $F_{\odot} = (S/4) \approx 341 \text{ W m}^{-2}$ , and  $T_{\oplus} = 255 \text{ K}$  (–18 C). Compared to Earth’s surface temperature of ~288 K (15 C), this corresponds to a ‘greenhouse effect’ of ~33 C.

Studies of Earth’s future climate (e.g. Goldblatt & Watson, 2012), or those estimating runaway greenhouse conditions for hotter or closer planets, are based on atmospheric models as a function of incident irradiation,  $F_{\text{ir}}$ . The models of Leconte et al. (2013b), for example, show that as the flux increases, Earth would undergo a decrease in surface albedo due to the melting of the permanent polar ice caps and the reduced seasonal snow cover. Above  $F_{\text{ir}} = 350 \text{ W m}^{-2}$ , seasonal ice caps only appear during the polar night, and the amount of H<sub>2</sub>O-vapour also increases. This results in a more efficient absorption of stellar irradiation, but also in an enhanced greenhouse effect which tends to homogenise the surface temperatures. Above  $F_{\text{ir}} = 375 \text{ W m}^{-2}$ , thermal emission reaches its limiting value,  $F_{\text{rg}}$ , and increasing surface temperatures mark the onset of the runaway greenhouse instability.

The complexities of current atmospheric models is seen, for example, in the work of Kopparapu et al. (2013).

from long-lived radionuclides, such as U<sup>235</sup>, U<sup>238</sup>, and K<sup>40</sup>, as on Earth (cf. Heppenheimer, 1978), and by the depression of the freezing point for brines (Möhlmann, 2012). Energy from the annihilation of dark matter has been suggested (Hooper & Steffen, 2012).

In the absence of any knowledge about a planet’s atmosphere, only the planet’s equilibrium temperature can be estimated from the inferred incident flux (§6.24.2). The equilibrium temperature will be increased, often significantly, by the trapping of radiation within its atmosphere. For terrestrial-type atmospheres, this includes contributions from the so-called ‘greenhouse gases’, i.e. those that absorb and emit radiation within the thermal infrared range; in Earth’s atmosphere, the most abundant greenhouse gases are, in decreasing importance, H<sub>2</sub>O-vapour, CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, O<sub>3</sub>, and chlorofluorocarbons (CFCs).

For Earth-like planets orbiting main-sequence stars, Kasting (1988) found an almost constant inner boundary defined by water loss and the runaway greenhouse

effect (box, page 619), as exemplified by the CO<sub>2</sub>-rich atmosphere and resulting temperature of Venus (Rasool & de Bergh, 1970). The more extended outer boundary (Kaltenegger & Selsis, 2007; von Paris et al., 2013a) is determined by the onset of CO<sub>2</sub> condensation, increasing planetary albedo, and runaway glaciation (Figure 11.37).

Kasting et al. (1993) used a 1d climate model to further characterise the inner and outer edges of the stellar habitable zone. Their basic premise was that of an Earth-like planet with a CO<sub>2</sub>/H<sub>2</sub>O/N<sub>2</sub> atmosphere, for which habitability requires liquid water on the planet's surface. The inner edge of the habitable zone is determined in their model by H<sub>2</sub>O loss via photolysis (§11.4.1) and H escape, while the outer edge is determined by the formation of CO<sub>2</sub> clouds, which cool a planet's surface by increasing its albedo and by lowering the convective lapse rate. These considerations resulted, for a 1 M<sub>☉</sub> star, in an inner boundary at ~0.75–0.95 au, and an outer boundary at ~1.37–1.77 au (Figure 11.38).

**Other climate modelling** Kopparapu et al. (2013) used a 1d radiative–convective climate model to estimate habitable zone widths around F, G, K, and M stars, employing new H<sub>2</sub>O and CO<sub>2</sub> absorption coefficients. They found H<sub>2</sub>O-loss (inner) and maximum greenhouse effect (outer) limits for the solar system's habitable zone at 0.99 and 1.70 au, suggesting that Earth lies near to its inner boundary. Calculations were also made for stars with  $T_{\text{eff}} = 2600 - 7200$  K, with results in parametric form facilitating application to other systems.

Kopparapu et al. (2014) extended this work to provide estimates of habitable zones around stars with  $T_{\text{eff}} = 2600 - 7200$  K, and for planet masses 0.1 – 5 M<sub>⊕</sub>. Again assuming H<sub>2</sub>O-(inner) and CO<sub>2</sub>-(outer) dominated atmospheres, and scaling the background N<sub>2</sub> atmospheric pressure with  $R_p$ , their results indicate that larger planets have wider habitable zones than smaller ones. Specifically, the inner edge of the habitable zone moves slightly outward for low-mass planets, due to a larger greenhouse effect arising from the increased H<sub>2</sub>O column depth. For larger planets, the H<sub>2</sub>O column depth is smaller, higher temperatures are needed before H<sub>2</sub>O vapour dominates the outgoing infrared radiation, and the inner edge moves slightly inwards. The outer limit is largely unaffected, due to the competing influence of the greenhouse effect and increased albedo.

The climate and, hence potential habitability of a planet depend crucially on how its atmospheric and ocean circulation transports heat from warmer to cooler regions. Global mean 1d models aiming to define the 'classical habitable zone' were accordingly followed by the new generation of 3d atmospheric (climate) models, tested on bodies in the solar system (box, page 593).

Such analyses are refining habitable zone boundary estimates, including effects of cloud cover, climate feedback, atmospheric pressure, snowball states and limit

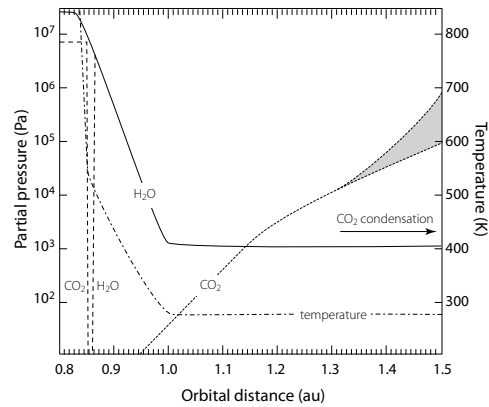


Figure 11.37: The partial pressures of CO<sub>2</sub> and H<sub>2</sub>O (left axis) and mean surface temperature (right axis) as a function of orbital distance for a habitable planet within the habitable zone. From Kaltenegger & Selsis (2007, Figure 2).

cycles, and outgassing (e.g. Selsis et al., 2007; Spiegel et al., 2008; Shaviv et al., 2011; Boschi et al., 2013; Forget, 2013; Kopparapu et al., 2013; Leconte et al., 2013b; Lucarini et al., 2013; Pinotti, 2013; Seager, 2013; Shields et al., 2013; Vladilo et al., 2013; Wordsworth & Pierrehumbert, 2013; Kopparapu et al., 2014; Wolf & Toon, 2013a, 2014; Abbot, 2016; Godolt et al., 2016; Haqq-Misra et al., 2016; Yang et al., 2016a; Kitzmann, 2017).

Leconte et al. (2013b) introduced dynamical and cloud feedback, key stabilising features of Earth's climate. They used the 3d LMD general circulation model (using the 3d 'dynamical core' of the LMDZ Earth model used in IPCC studies) to show that the insolation threshold for the onset of the runaway greenhouse state is about 375 W m<sup>-2</sup>, somewhat higher than previous (1d-model) estimates, although still corresponding to an inner habitable zone boundary close to 0.95 au, where the solar flux is ~1.1 times that at Earth.

Planetary surface conditions, affecting the albedo, include the land/ocean fraction (Spiegel et al., 2008), effects of snow and ice, including albedo feedback (Tajika, 2008; Joshi & Haberle, 2012; von Paris et al., 2013c; Shields et al., 2014), and the closer inner edge in the case of 'hot desert' worlds (Zsom et al., 2013).

Atmospheric models with simplified ocean treatment have since included more detailed models. Cullum et al. (2014) introduced a simple (meridional) 'continental barrier', finding that the poleward ocean heat transport increases significantly as rotation period increases, with additional significant changes to ocean temperature at depth, with implications for the carbon cycle.

**Other orbit effects** Various other orbit effects play a role in defining the habitable zone, including eccentricities (Williams & Pollard, 2002; Selsis et al., 2007; Barnes et al., 2008c; Dressing et al., 2010; Kita et al., 2010; Kane & Gelino, 2012b; Bolmont et al., 2016; Méndez & Rivera-Valentín, 2017), and long-term Milankovitch-type cycles



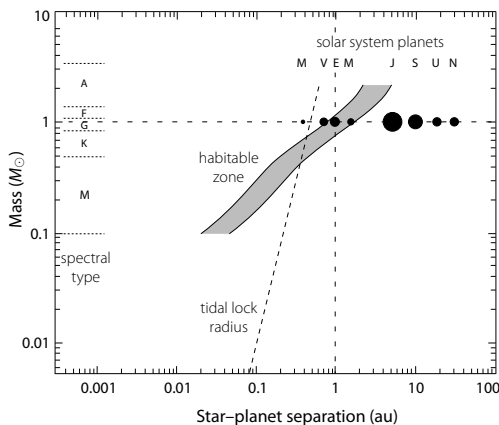


Figure 11.38: The habitable zone, within which a planet can maintain liquid water on its surface as a consequence of the star's mass and luminosity. Earth sits within the habitable zone, while Venus and Mars are located at its edges. The dotted line indicates the distance at which an Earth-like planet in a circular orbit would be in synchronous rotation within 4.5 Gyr as a result of tidal damping. Earth-like planets within the habitable zone of an  $M$  star would be within this tidal-lock radius. From Kasting et al. (1993, Figure 16), with permission from Elsevier.

(Spiegel et al., 2010b; Markonis & Koutsoyiannis, 2013; Rosengren & Scheeres, 2014; Forgan, 2016; Deitrick et al., 2018, see also footnote, page 681). Williams & Pollard (2002), for example, used a 3d climate model and a 1d energy-balance model to argue that, for large  $e$ , climate stability depends primarily on the average stellar flux over the orbit, rather than the duration spent within the habitable zone (cf. Figure 11.40).

Other work has considered orbit evolution due to tides (Barnes et al., 2008c; Heller et al., 2011a; Brasser et al., 2013a), the effects of planet obliquity (Spiegel et al., 2009a; Heller et al., 2011b; Armstrong et al., 2014b; Ferreira et al., 2014; Kane & Torres, 2017; Kilic et al., 2017; Rose et al., 2017; Nowajewski et al., 2018), and related diurnal and seasonal effects (von Bloh et al., 2010).

In the solar system explicitly, Jupiter has a major effect on the eccentricity and obliquity states of Mars and its climate (Ward & Rudy, 1991; Armstrong et al., 2004; Laskar et al., 2004), and Jupiter also has an effect on Earth as part of the Milankovich cycles. The role of Earth's large Moon in stabilising its obliquity in the face of Jupiter's influence is detailed in Section 12.3.3. Way & Georgakarakos (2017) considered the climate of an Earth-like world in the absence of Mars, and a Jupiter-like planet closer to Earth.

**M dwarfs and spin-orbit resonance** Their abundance makes nearby  $M$  dwarfs important targets in the search for habitable planets. However, at least two complications specific to  $M$  dwarfs arise when considering their potential habitability: the effects of tidal locking, and the effects of stellar chromospheric activity.

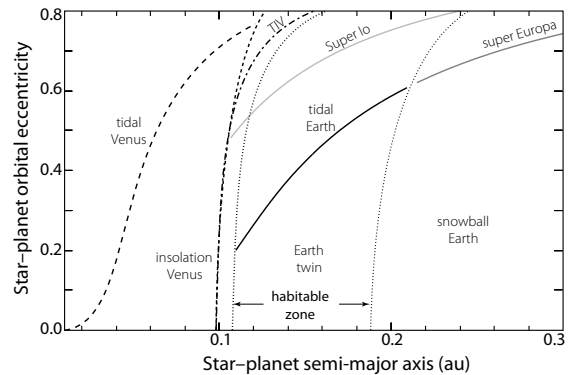


Figure 11.39: Habitable and uninhabitable terrestrial planets based on stellar irradiation and tidal heating, assuming  $M_p = 1.5M_\oplus$  and  $R_p = 1.12R_\oplus$  around a star similar to GJ 581. Dotted lines are habitable zone boundaries estimated by Kopparapu et al. (2013), with an inner edge defined by runaway greenhouse, and an outer by the maximum greenhouse effect. Tidal heating can extend the conventional habitable zone, with liquid  $H_2O$  existing well beyond 0.2 au for a tidally-heated super-Europa. Adapted from Heller & Armstrong (2014, Figure 1).

The habitable zone of  $M$  dwarfs, determined by the orbital distance at which  $H_2O$  is likely to be liquid, is  $\sim 0.1$  au (Kasting et al., 1993; Kopparapu et al., 2013). At these small separations, planets are locked in spin-orbit resonance by strong tidal forces (§10.11). For orbits of low eccentricity, the 1:1 resonance state (synchronous rotation) is the most likely configuration, such that one side of the planet permanently faces the host star.

Many studies have examined the associated stellar insolation, tidal heating, atmospheric circulation (and the probability of cyclones), the effect of near-resonant companions on their spin state, and other effects (e.g. Dole, 1964; Kasting et al., 1993; Joshi & Haberle, 1997; Joshi et al., 1997; Joshi, 2003; Tarter et al., 2007; Edson et al., 2011; Kite et al., 2011; Heng & Kopparla, 2012; Mills & Abbot, 2013; Yang et al., 2013; Carone et al., 2014; Yang & Abbot, 2014; Newton et al., 2016; Proedrou & Hocke, 2016; Shields et al., 2016; Wang et al., 2016c; Barnes, 2017; Checlair et al., 2017; Kopparapu et al., 2017; Vinson & Hansen, 2017; Yates et al., 2017; Bin et al., 2018; Haqq-Misra et al., 2018b).

**Eyeball climate patterns** General circulation models have identified the robust appearance of an 'eyeball' climate pattern, with a limited 'pupil' area of open ocean centred at the substellar point, and ice coverage on the night-side, which persists even with a strong greenhouse effect and stellar radiation (e.g. Dobrovolskis, 2007, 2009; Edson et al., 2011; Heng et al., 2011b; Heng & Vogt, 2011; Pierrehumbert, 2011a; Wordsworth et al., 2011; Edson et al., 2012; Dobrovolskis, 2013b; Menou, 2013; Yang et al., 2013; Hu & Yang, 2014; Wang et al., 2014g; Dobrovolskis, 2015a; Zhang et al., 2017c). GJ 581 g was amongst those intensively studied as the first terrestrial mass planet discovered in the habitable zone, although its existence has since been questioned (see Appendix C).

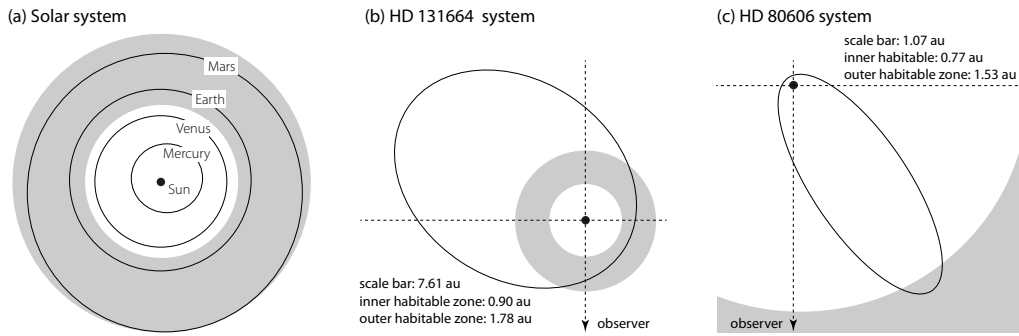


Figure 11.40: Orbits and habitable zones (shaded) for some illustrative systems: (a) the inner solar system; (b) the HD 131664 system. (c) the HD 80606 system. Adapted from Kane & Gelino (2012b, Figures 1, 4, 5).

**Effects of eccentricity and obliquity** Large eccentricities lead to both a large contrast in incident flux between apocentre and pericentre, as well as modification of the spin-orbit resonance states (Dressing et al., 2010; Kataria et al., 2013; Wang et al., 2014g; Linsenmeier et al., 2015).

Non-zero eccentricities can frequently result in a ‘striped ball’ climate pattern, with a global belt of open water at low latitudes, and ice over both polar regions (Wang et al., 2014g); distinguishing between ‘eyeball’ and ‘striped ball’ patterns could be possible with JWST for nearby planets such as GJ 667C c. The long-term build-up of ice (or liquid) away from the insolation hot spots may alter the planet’s inertia tensor and quadrupole moments enough to re-orient the planet (Dobrovolskis, 2015a).

Corresponding effects for solar system objects (§12.4.6), due to climate feedback and volatile migration, have been considered for the long-term axial tilt and present obliquity of Mars (Rubincam, 1990, 1993); for Earth (Bills, 1994); and for Triton and Pluto (Rubincam, 2003). Williams & Pollard (2002) found that the Earth would remain habitable if its eccentricity was 0.4.

**Other effects** Detailed tidal models suggest that even a relatively thin atmosphere can drive terrestrial planet rotation away from synchronicity (Leconte et al., 2015b), with the implication that not all terrestrial habitable zone planets around M dwarfs are in a spin-synchronised state, especially in the outer habitable zone where planets may include massive CO<sub>2</sub> atmospheres (Figure 11.41).

Many other effects influence details of the habitable zone. There is a dependence of the inner edge on planet rotation and land distribution (Leconte et al., 2013a; Zalucha et al., 2013; Yang et al., 2014a; Kopparapu et al., 2016), while the outer edge is affected by the reduced albedo of snow and ice at  $\lambda > 1 \mu\text{m}$  (Joshi & Haberle, 2012).

Other studies have considered effects of the stellar magnetic field as a function of stellar rotation (Vidotto et al., 2013; Gallet et al., 2017b); effects on the magnetospheric structure and ionospheric Joule heating due to stellar winds (Cohen et al., 2014); effects of planetary tidal heating on mantle melting and the resulting extended duration of the habitable zone occupation (Shoji & Kurita, 2014); the effects of water-trapping in ice sheets on the night-side, and the resulting effects of desiccation on the day-side (Yang et al., 2014b); and enhanced atmospheric photoevaporation which may transform Kepler’s small gaseous ‘mini-Neptunes’ into habitable super-Earths (Luger et al., 2015; Owen & Mohanty, 2016).

**Occurrence** Kepler provides detailed insights into the occurrence of habitable zone planets around M dwarfs (Dressing & Charbonneau, 2015). ‘Optimistic’ insolation boundaries yield  $0.24^{+0.18}_{-0.08}$  Earth-size ( $1 - 1.5R_{\oplus}$ ) planets and  $0.21^{+0.11}_{-0.06}$  super-Earths ( $1.5 - 2.0R_{\oplus}$ ) per M dwarf habitable zone. This suggests that the nearest potentially habitable *transiting* Earth-size planets is  $10.6^{+1.6}_{-1.8}$  pc distant, or  $8.6^{+0.7}_{-0.8}$  pc including super-Earths. For *non-transiting planets*, these proximity distances decrease to  $2.6 \pm 0.4$  pc and  $2.1 \pm 0.2$  pc respectively.

Planets may even be observable in a time-evolving zone of pre-main sequence M dwarfs (Tian, 2015c).

**Other spin-orbit resonances** Spin-orbit resonances other than the 1:1 synchronised rotation are possible (see also §10.11.5). More generally, the spin-orbit resonance number is defined as  $p = (\omega/n)$ , where  $\omega$  and  $n$  are the spin and orbital mean angular velocities. A solid exoplanet can be locked into any spin-orbit resonance state, with  $p$  being equal to an integer or a half integer (Murray & Dermott, 2000; Dobrovolskis, 2007). For example, the Moon has  $e = 0.05$  and  $p = 1$ , while Mercury has  $e = 0.2$  and  $p = 1.5$ . For the potentially habitable planets GJ 581 d and GJ 667C c, it was estimated that the most likely resonance states are  $p = 2$  (Makarov et al., 2012) and  $p = 1.5$  (Makarov & Berghea, 2014), respectively.

Probabilities of a given resonance state, for different eccentricities and initial spin states, can be calculated following the methods given by, e.g., Dobrovolskis (2007). Such models show that the most likely resonance state for a planet with low eccentricity is  $p = 1$ , while for rapidly spinning planets with  $0.15 < e < 0.3$  and  $0.3 < e < 0.4$ , the most likely resonance states are  $p = 1.5$  and  $p = 2$ , respectively. For slowly spinning planets with  $0.33 < e < 0.44$ , the most likely resonance state is  $p = 1.5$ . Asynchronous spin-orbit resonance states as a function of planet triaxiality are detailed by Zanazzi & Lai (2017c).

The time scales for capture into such spin-orbit resonance states are short. The decaying eccentricity time scale for an Earth-mass and Earth-size planet at 0.1 au around a  $0.3M_{\star}$  star is about 3.6 Gyr, assuming a tidal dissipation factor  $Q = 10$ , similar to that of Earth (Goldreich & Peale, 1966; Rasio et al., 1996). In contrast, the time scale for an exoplanet to be captured into spin-orbit resonance states, including the synchronous rotation state  $p = 1$ , is some 7000 yr (Guillot et al., 1996; Rasio et al., 1996). Accordingly, habitable exoplanets in eccentric orbits with various spin-orbit resonance states should be common.

Habitable zones and climate models corresponding to eccentric orbits and 2:1 (Wang et al., 2014g) or higher (Dobro-

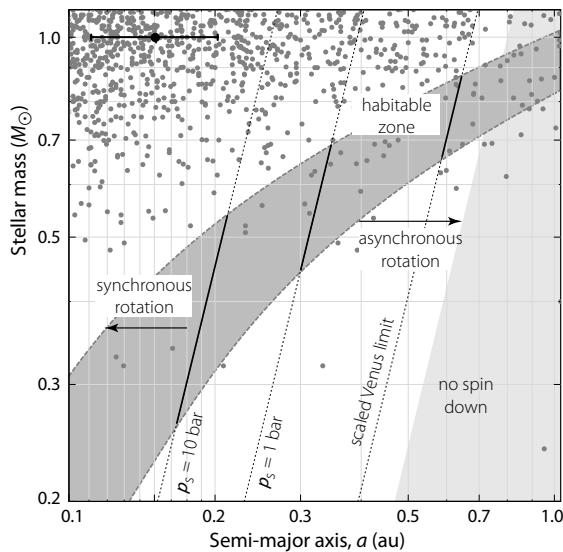


Figure 11.41: Spin state of planets in the habitable zone. Solid black line marks the critical orbital distance (their equation 4) separating synchronous from asynchronous planets for surface pressures  $p_s = 1$  and  $10$  bar ( $10^6/10^7$  Pa; extrapolation outside the habitable zone is dotted). Objects in the light grey area are not spun down by tides. The habitable zone is shaded dark grey. Small circles are detected and candidate exoplanets. The error bar indicates how limits change when varying the tidal dissipation term ( $Q \sim 100$ ) by a factor 10. From Lecante et al. (2015b, Figure 3), reprinted with permission from AAAS.

volskis, 2015a) spin-orbit resonances show more complex patterns. For example, Dobrovolskis (2015a) found that, for negligible obliquities and the 0:1, 1:2, 1:1, 3:2, 2:1, 5:2, 3:1, 7:2, and 4:1 spin-orbit resonances, the mean insolation is distributed in a similar ‘eyeball’ pattern for integer resonances, while for half-odd resonances, the mean insolation shows a ‘double-eyeball’ pattern, identical over east and west hemispheres.

**Chromospheric activity** Strong chromospheric activity of M dwarfs produces high-energy radiation, stellar winds, and charged particles that may be detrimental to life (e.g. Zendejas et al., 2010; Vidotto et al., 2014). Segura et al. (2010) considered the effect of such a high-energy flare on the magnetically-active AD Leo, simulating the effects from both ultraviolet radiation and protons on the atmospheric chemistry of a hypothetical Earth-like planet within its habitable zone. Results indicate that the ultraviolet radiation does not produce a significant change in the  $O_3$  column depth of the planet, with  $O_3$  depletion reaching a maximum of 94% two years after the flare for a planet with no magnetic field. At the peak of the flare, the ultraviolet fluxes that reach the surface, in the wavelength ranges that are damaging for life, exceed those received on Earth for less than 100 s.

**Binary star systems** The boundaries of the habitable zone are further complicated for planets in binary or multiple star systems, where both radiative and gravitational perturbations must be accounted for. Various studies have been made, both for circumbinary (P-type) planets and circumprimary (S-type) planets in general, as well as for specific systems.

For circumbinary planets, the habitable zone is determined by each star’s contribution to the total flux. The resulting habitable zones are often ‘dynamic’ and, depending on the binary eccentricity and the component luminosities and spectral types, their boundaries vary as the stars sweep out their orbits (Harrington, 1977; Harrington & Harrington, 1978; Haghighipour & Kaltenegger, 2013; Jaime et al., 2014; Cuntz, 2014, 2015; Popp & Eggl, 2017). The effects of secular resonances for close-separation binaries have also been detailed (Bazsó et al., 2017).

Specific studies have examined the habitable zones of the Kepler circumbinary planets, including those around Kepler-16, Kepler-34, Kepler-35, Kepler-38, Kepler-47 and Kepler-64, with the typical goals of identifying where a stable, habitable, Earth-like planet might exist (e.g. Kane & Hinkel, 2013; Liu et al., 2013b; Mason et al., 2013; Forgan, 2014; Wang & Cuntz, 2017).

Similar considerations apply to S-type systems, where studies find a strong dependence of permanent habitability on the binary’s eccentricity, as well as a possible extension of habitable zones towards the secondary in close binary systems (Eggl et al., 2012, 2013b; Kaltenegger & Haghighipour, 2013; Cuntz, 2014, 2015; Wang & Cuntz, 2017). An interactive model, developed to address the specifics of individual systems, is described by Müller & Haghighipour (2014).

Circumbinary planets with particular parameters, specifically around main-sequence binaries, might be particularly favourable for habitability from the perspective of insolation, seasons, presence of water, climate stability, tidal phenomena, protection from extreme ultraviolet radiation and stellar wind, and active tectonics (Mason et al., 2013, 2015b,a; Zuluaga et al., 2016; Shevchenko, 2017a). Shevchenko (2017a) has suggested that most of the production of replicating biopolymers in the Galaxy is concentrated in particular classes of circumbinary planets around main-sequence stars, and that life on Earth is, in this sense, an outlier.

**Multi-planet systems** The overall architecture determines the likelihood of planets in multi-planet systems remaining within the habitable zone over extended periods (e.g. Jones et al., 2001; Goździewski, 2002; Jones & Sleep, 2002; Noble et al., 2002; Dvorak et al., 2003a,b; Menou & Tabachnik, 2003; Asghari et al., 2004; Érdi et al., 2004; Jones et al., 2005; Fatuzzo et al., 2006; Haghighipour, 2006; Jones et al., 2006a; Laakso et al., 2006; Sándor et al., 2007b; von Bloh et al., 2007b; Hinse et al., 2008; Ji et al., 2008; Pilat-Lohinger et al., 2008a,b; Cuntz & Yeager, 2009; Smith & Lissauer, 2009; Dvorak et al., 2010b; Kopparapu & Barnes, 2010; Funk et al., 2011a).

As examples of this considerable body of work, Menou & Tabachnik (2003) and Jones et al. (2006a) determined the borders of the zero-age main sequence and present habitable zones, respectively. In systems with a

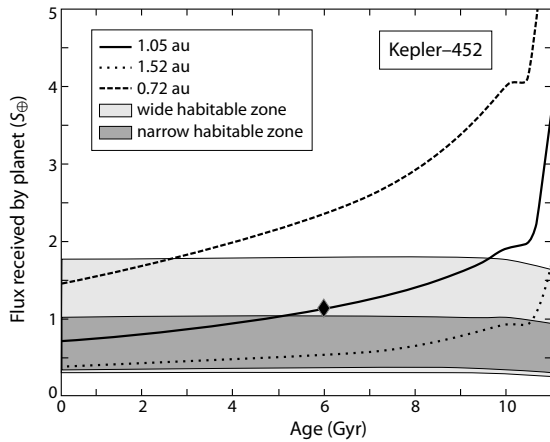


Figure 11.42: History of the habitable zone of Kepler-452 as inferred from the flux received by a planet at the orbital distance of Kepler-452 b (1.05 au) over the star's main-sequence lifetime. The radiation received by the planet from 0.25 to 11 Gyr is shown by the solid curve. The optimistic and conservative habitable zones, according to Kopparapu et al. (2013), are indicated by the light and dark grey shaded regions. The planet currently experiences radiation levels 10% above that of Earth. However, over the first 5.2 Gyr of its history, Kepler-452 b was in the conservative habitable zone, receiving less than 1.03 of the flux received by contemporary Earth. Dotted and dashed curves represent the flux received by planets in the orbits of Mars and Venus (1.52 and 0.72 au), respectively. From Jenkins et al. (2015, Figure 16), by permission of IOP Publishing/AAS.

giant planet, Sándor et al. (2007b) determined stability maps to help establish where Earth-like planets could exist (§2.12.7). Further consideration of *resilient habitability* in systems with a giant planet have assessed the long-term stability of planets in the associated habitable zone (Carrera et al., 2016).

Habitability of Trojan planets, in single and binary systems, have been considered explicitly (Eberle et al., 2011; Funk et al., 2012; Schwarz et al., 2015b, 2017).

**Continuously habitable zone** The habitable zone moves outwards with time, dependent on stellar mass, because of increasing stellar luminosity with age. This results in a somewhat narrower *continuously habitable zone*, loosely defined as the range of orbital distance over which liquid H<sub>2</sub>O could have existed continuously over whatever period of time is necessary for the evolution of life (Hart, 1978, 1979; Underwood et al., 2003; Oishi & Kamaya, 2016a). Such modeling, for Kepler-452, is shown in Figure 11.42.

The Sun's continuously habitable zone over the past 4 Gyr lies between 0.95–1.15 au. Positive feedback due to the greenhouse effect and planetary albedo variations, and negative feedback due to the link between atmospheric CO<sub>2</sub> level and surface temperature, via the carbonate–silicate cycle (§12.3.5), modify these boundaries (Kasting, 1988; Kasting et al., 1993; Kasting, 1996).

While Earth's habitability over early geological time is complex and incompletely understood (§12.3.8), its climate has remained conducive to life for the past 3.5 Gyr years or more, perhaps since as early as 10–20 Myr after the Moon-forming impact (Hart, 1978; Martin et al., 2006a,b; Zahnle et al., 2007), despite a large increase in solar luminosity over this period (the 'faint young Sun paradox', §12.3.8). Previous higher concentrations of CO<sub>2</sub> and/or CH<sub>4</sub>, combined with negative feedback loops, may have helped to stabilise the climate (Kasting & Catling, 2003, see also §11.4.3). Such effects may have been sufficient to accommodate the 30% increase in the Sun's luminosity over the last 4.6 Gyr needed in order to sustain the continuous presence of liquid water evident from geological records (Kasting, 1996; Lean & Rind, 1998; Lunine, 1999a,b).

**Future of Earth's habitable zone** Runaway greenhouse conditions on Earth, e.g. as a result of increasing (anthropogenic) atmospheric greenhouse gases such as CO<sub>2</sub>, have been modeled, and appear unlikely (e.g. Goldblatt & Watson, 2012). For the more distant future of the solar system's habitable zone, the Sun will grow progressively brighter over its main sequence lifetime, by ~10% over the next 1.1 Gyr, reaching three times its present luminosity when it leaves the main sequence in ~5 Gyr.

Earlier 1d climate models suggested that catastrophic thermal runaway will be triggered by a ~6% increase in the solar constant, with the Earth leaving the continuously habitable zone in some 500–900 Myr (Caldeira & Kasting, 1992). Using a 3d climate model, with fixed CO<sub>2</sub> and CH<sub>4</sub>, Wolf & Toon (2014) showed that habitability may be maintained at significantly larger solar constants. A 15% increase yields global mean surface temperatures of 313 K, still well short of moist and runaway greenhouse states, for at least another 1.5 Gyr.

The persistence of unicellular life, in the form of *swan-song biospheres*, for up to 2.8 Gyr has been estimated (O'Malley-James et al., 2013, 2014).

**Hydrogen greenhouse warming** Planets of 1–20 M<sub>J</sub> can form with primordial H<sub>2</sub> envelopes, either due to capture from the solar nebula (Rafikov, 2006), or outgassing during accretion (e.g. Elkins-Tanton & Seager, 2008b). In the case of Earth and Venus, these envelopes may have been lost to space extremely rapidly, while planets in more distant orbits, or those ejected into interstellar space during formation, can retain them indefinitely (Stevenson, 1999; Pierrehumbert & Gaidos, 2011).

In these cases, an additional heat source arises from the pressure-induced far-infrared opacity (collision-induced absorption) of H<sub>2</sub>. Even for  $T_{\text{eff}} = 30$  K, atmospheric basal temperatures can exceed the melting point of water (Stevenson, 1999). This effect, most relevant for gas giants, could significantly extend the habitable zone in G and M dwarfs in the case of cyanobacteria or anoxygenic phototrophs (Pierrehumbert & Gaidos, 2011; Seager et al., 2013a,b; Abbot, 2015). and similarly for CO<sub>2</sub>-rich atmospheres (Neubauer et al., 2013).

In the intermediate situations where H<sub>2</sub> atmospheres persist for some time after formation but are eventually removed, transient periods will occur where water exists as a liquid on the planet's surface, and organic molecules may form in the atmosphere via photochemistry (Wordsworth, 2012).

**Other evolutionary phases** Lopez et al. (2000, 2005) considered the development of the habitable zone at much larger distances, 5–50 au, during the short period of post-main-sequence

evolution corresponding to the subgiant and red giant phases. Other estimates have been made at earlier and later stages of Earth's evolution (O'Malley-James et al., 2015; Arney et al., 2016); for pre-main-sequence stars (Ramirez & Kaltenegger, 2014); for low-mass stars (Valle et al., 2014); for brown dwarfs and white dwarfs (Barnes & Heller, 2013; Loeb & Maoz, 2013); and for stars ranging from pre-main-sequence to the asymptotic giant branch as a function of metallicity (Danchi & Lopez, 2013). As an example, Ramirez & Kaltenegger (2016) found that planets can remain up to 9 Gyr in the post-main sequence habitable zone, that total atmospheric erosion only occurs for planets in close-in orbit, and that these orbital distances are within the detection capability of current direct imaging techniques.

**Galactic habitable zone** Gonzalez (1999a) investigated implications of the small motion of the Sun with respect to the local standard of rest, both in terms of its pseudo-elliptical component within the Galactic plane, and its vertical excursion with respect to the mid-plane. Such an orbit may provide effective shielding from high-energy ionising photons and cosmic rays from nearby supernovae, from the X-ray background by neutral hydrogen in the Galactic plane, and from temporary increases in the perturbed Oort comet impact rate.

Various subsequent assessments of the extent of the *Galactic habitable zone* have been attempted, accounting for various effects including chemical evolution models for the Milky Way disk and dust-to-gas ratios in the interstellar medium (e.g. Gonzalez et al., 2001a; Lineweaver et al., 2004; Ćirković & Bradbury, 2006; Cole, 2006; Bounama et al., 2007; Vukotić, 2010; Lineweaver & Chopra, 2012; Spitoni et al., 2017), with Prantzos (2008) concluding that the physical processes underlying the concept of a Galactic habitable zone are '*hard to identify and even harder to quantify*'.

Later models included effects of supernova rates (SN Ia and SN II) and their associated 'sterilising' effects, planet formation, tidal locking, and the time required for complex life to evolve. Gowanlock et al. (2011) estimated that ~1% of all stars may have been capable of supporting complex life at some point in the history of the Galaxy, that 75% of stars with a habitable planet are predicted to be tidally locked, and that the majority of planets that may support complex life are found towards the inner Galaxy, distributed within, as well as significantly above and below, the Galactic mid-plane.

Horvath & Galante (2012) assessed the effects of four transient sources of ionising radiation on biospheres, viz. stellar flares, giant flares from soft gamma repeaters, supernovae, and  $\gamma$ -ray bursts. More restricted zones may result from disruption in cluster environments (de Juan Ovelar et al., 2012). Galactic habitable zones have also been considered for elliptical galaxies (Suthar & McKay, 2012), as well as for M31 (Carigi et al., 2013).

If chiral asymmetry is also a prerequisite for life (e.g. Bailey, 2000, 2004; Gleiser & Walker, 2012), habitability may further depend on the polarisation environment of the star forming region.

**Globular clusters** Globular clusters may be favourable habitable environments, with no star formation, no core-collapse supernovae, regions in which habitable zone planet orbits are stable for long times, and with interstellar distances typically far smaller than in the Galactic disk, facilitating interstellar communication and travel (Di Stefano & Ray, 2016).

**Pulsar planets** Patruno & Kama (2017) considered the effect of X-ray irradiation and the relativistic pulsar wind on pulsar planet atmospheres, and their survival time. For a habitable zone defined by the presence of liquid water and retention of an atmosphere, they suggest that both super-Earths around PSR B1257+12 (S4.2.2) could lie within its habitable zone, depending on poorly constrained aspects of the pulsar wind.

**Beyond our Galaxy** Coupling a galaxy formation model with a dependency of planet formation on host star metallicity and mass, Zackrisson et al. (2016) deduced that the typical terrestrial planet is in a spheroid-dominated galaxy of Milky Way mass, that the mean age of terrestrial planets in the local Universe is  $7 \pm 1$  Gyr and  $8 \pm 1$  Gyr for FGK and M dwarf hosts respectively, and that the total inventory of terrestrial planets in the observable Universe is  $\sim 10^{19}$  and  $\sim 5 \times 10^{20}$  respectively. Go bat & Hong (2016) used a galaxy evolution model to estimate that: (1) the fraction of stars with terrestrial planets in their habitable zone depends only weakly on galaxy mass, with a maximum at  $4 \times 10^{10} M_{\odot}$ ; (2) 0.7% of all stars in Milky Way-type galaxies host a terrestrial planet within their habitable zone, consistent with the value derived from Kepler; (3) overall habitability of galaxies has not changed significantly in the last 8 Gyr, with most habitable planets in local disk galaxies having formed ~1.5 Gyr before the solar system; and (4)  $1.4 \times 10^9$  planets similar to present-day Earth have existed so far in the Galaxy.

**The most habitable galaxies** Dayal et al. (2015) assessed the most habitable type of galaxy. They invoked the SDSS 'fundamental metallicity relation' to link three key astrophysical criteria governing habitability (total mass in stars, total metal mass, and ongoing star formation rate) to show that metal-rich, shapeless giant elliptical galaxies at least twice as massive as the Milky Way, with one tenth of its star formation rate, can potentially host ten thousand times as many habitable (Earth-like) planets, making them the most probable 'cradles of life' in the Universe. A factor 10 more planets will exist in the future if existing gas within virialised dark matter haloes continues to collapse and form stars and planets (Behroozi & Peebles, 2015).

**Beyond our Universe** Adams et al. (2015) assessed the types of structure that could form in other universes, perhaps as part of a multiverse, with alternate values of the fluctuation amplitude,  $Q$ . If  $Q$  is too small, cosmological structure has difficulty forming, and the resulting objects could be too rarified to cool and form stars, and too loosely bound to retain the heavy elements produced by stars. If  $Q$  is too large, then galaxies are much denser than those of our Universe, and can be too dense to allow planet orbits to remain unperturbed over the long times necessary for biological evolution.

Universes with a slightly weaker strong force, in which deuterium is unstable and standard nucleosynthesis is compromised, may still be habitable (Adams & Grohs, 2017).

### 11.7.2 Tidal heating

Tidal heating is an important additional heat source for many exoplanets (§10.11.9). It could have significant implications for habitability, and a number of detailed assessments have been (e.g. Jackson et al., 2008a,c; Barnes et al., 2009b; Leconte et al., 2010a; Van Laerhoven et al., 2014; Driscoll & Barnes, 2015).

**Relevance in the solar system** In the solar system, tidal heating of Jupiter's moon Io is driven by the temporally periodic, spatially differential projection of Jupiter's gravitational field (§10.11.9). It has been suggested that the chemicals required for life could be generated by energetic charged particles trapped in Jupiter's magnetosphere (Johnson et al., 2004), and transported into the subsurface ocean by impacts (Chyba & Phillips, 2002), or local melting (O'Brien et al., 2002). Tidal heating might also give rise to underwater volcanic vents (O'Brien et al., 2002), which could support life directly with thermal energy, by analogy with the deep ocean thermophilic bacteria found on Earth (Baross, 1983).

The Jovian satellite Europa is a rocky body covered by 150 km of H<sub>2</sub>O, for which tidal heating may maintain a subsurface water ocean and which, scaling from the tidal heating on Io, may have a surface ice layer only a few km thick (Greenberg, 2005). Tidal heating of an icy exoplanet may similarly generate a subsurface ocean suitable for life, even in the absence of an atmosphere (Reynolds et al., 1983; Chyba, 2000; Greenberg, 2005; Vance et al., 2007).

**Example cases** Heller & Armstrong (2014) illustrate the effects of tidal heating for the case  $M_p = 1.5M_\oplus$  and  $R_p = 1.12R_\oplus$  and a host star similar to GJ 581. With stellar irradiation  $F_{\text{ir}}$ , tidal heat flux  $F_t$ , and the critical flux for the onset of runaway greenhouse  $F_{\text{rg}}$  (box, page 619), they estimate  $F_{\text{rg}} = 301 \text{ W m}^{-2}$  from the analytical expressions of Pierrehumbert (2011b), with the habitable zone boundaries as modeled by Kopparapu et al. (2013).

In their models, uninhabitable worlds (Figure 11.39) include a tidal Venus (with  $F_t \geq F_{\text{rg}}$ ), an insolation Venus (with  $F_t \geq F_{\text{rg}}$ ), a tidal-insolation Venus (with  $F_t \leq F_{\text{rg}}$ ,  $F_i \leq F_{\text{rg}}$ , and  $F_t + F_i \geq F_{\text{rg}}$ ), and a snowball Earth (with  $F_t \leq 0.04 \text{ W m}^{-2}$  and beyond the habitable zone). Potentially habitable worlds include a super-Io ( $F_t \geq 2 \text{ W m}^{-2}$  and  $F_t + F_i \leq F_{\text{rg}}$ , as hypothesised by Jackson et al. 2008c), a tidal Earth ( $0.04 < F_t \leq 2 \text{ W m}^{-2}$ ,  $F_t + F_i \leq F_{\text{rg}}$ , and within the habitable zone), and a super-Europa ( $0.04 < F_t \leq 2 \text{ W m}^{-2}$  and beyond the habitable zone), as well as an Earth twin ( $F_t < 0.04 \text{ W m}^{-2}$  and beyond the habitable zone).

**Contribution to tectonic activity** For the Earth, tidal heating is negligible, but internal energy from radionuclide decay and the residual heat of formation drives convection in the mantle, contributing to plate tectonic motion (O'Neill & Lenardic, 2007), and helping to

stabilise the atmosphere and surface temperature over hundreds of millions of years (Walker et al., 1981). If a stable surface temperature is a prerequisite for life, plate tectonics may be required for habitability (Regenauer-Lieb et al., 2001). When Mars was last tectonically active, its radiogenic heat flux was  $\sim 0.04 \text{ W m}^{-2}$  (Williams et al., 1997), perhaps a minimum amount required for tectonics in a rocky planet. For terrestrial planets with  $M > 1M_\oplus$ , O'Neill & Lenardic (2007) have argued that plate tectonics may be less likely, while Valencia et al. (2007a) concluded the opposite.

Henning et al. (2009) found that tidal heating tends to exceed radionuclide heating at orbital periods below 10–30 d, and to exceed insolation only below 1–2 d. For the periods and magnitudes considered, tidal heating generally decreases the width of habitable zones. Tidal heating can also affect the body's rheology (flow), with extreme cases leading to partial melting (Zahnle et al., 2007; Henning et al., 2009; Remus et al., 2012b).

M dwarf host stars are considered promising candidates for the discovery of Earth-like habitable planets, as a consequence of the smaller mass ratio required for radial velocity searches for any given planetary mass. Their lower masses imply that their habitable zones would lie closer to the host star than for more massive stars (Selsis et al., 2007; Tarter et al., 2007). However, if rocky planets around M stars have masses much less than  $1M_\oplus$  (Raymond et al., 2007b), then such planets may have too little radiogenic heating to drive long-lived plate tectonics (Williams et al., 1997).

In these circumstances, tidal heating may provide a significant heat source, and may be critical in determining habitability. At the opposite extreme, in analogy with the highly active Jovian satellite Io, terrestrial planets with even moderate eccentricities may have very high tidal heating, perhaps ruling out habitability as a result of excessive volcanic activity (Barnes et al., 2009b).

**Contribution to atmospheric replenishment** Planet atmospheres are in general believed to originate from a combination of accretion and outgassing (§11.4.3). Tidal heating can enhance the outgassing of volatiles in the mantle by increasing internal convection, and can supply or replenish atmospheres that might otherwise be lost by planetesimal erosion, thermal (Jeans) escape, and hydrodynamic escape (§11.4.5), further promoted by photolytic dissociation (§11.4.1).

With such scenarios in mind, Jackson et al. (2008a) modeled the tidal heating and evolution of a range of hypothetical exoplanets. They integrated the tidal equations over a range of stellar and planetary masses, assuming a planetary radius based on the geophysical models of Sotin et al. (2007), viz.  $R_p = M_p^{0.27}$  for  $1 < M_p < 10$  and  $R_p = M_p^{0.3}$  for  $0.1 < M_p < 1$ . Each planet was assigned an initial semi-major axis in the middle of its star's habitable zone (§11.7.1).

**Habitability of exomoons:** Rocky and icy exomoons are likely to exist around giant exoplanets (Sasaki et al., 2010; Ogihara & Ida, 2012). These planets will have their own *circumplanetary habitable zone*, beyond any stellar habitable zone, determined by planetary illumination, and supplemented by any tidal heating.

The solar system giants' moons serve as a guide. For all the Galilean satellites  $e_{\text{orb}} > 0.001$ , continually forced by their gravitational interaction with Jupiter (Yoder, 1979). Saturn's Titan's has  $e_{\text{orb}} = 0.029$ ; reasons for its large eccentricity remain unclear, although perhaps related to its formation (Sohl et al., 1995; Ćuk et al., 2016a).

Assessment of exomoon habitability, around both terrestrial and giant planets, includes effects of eclipses, runaway greenhouse, outgassing, shielding of the host's magnetosphere, multiple heat sources, and longevity (Reynolds et al., 1987; Williams et al., 1997; Kaltenecker, 2010; Porter & Grundy, 2011; Heller, 2012; Forgan & Kipping, 2013; Hinkel & Kane, 2013a; Heller et al., 2014; Lammer et al., 2014a; Sasaki & Barnes, 2014; Tokano, 2015; Heller & Barnes, 2015; Dobos et al., 2017; Sato et al., 2017). Atmospheric particle loss may be diminished if the moon has an intrinsic magnetic field, as for Ganymede (Kivelson et al., 1998).

Beyond the stellar habitable zone, tidal heating could support liquid H<sub>2</sub>O (§11.7.2), at or below the surface (Reynolds et al., 1987; Scharf, 2006; Henning et al., 2009; Heller & Barnes, 2013; Forgan & Yotov, 2014; Heller & Armstrong, 2014; Dobos & Turner, 2015), while excessive heating will render others uninhabitable (Zollinger et al., 2017).

Examples for two different planet–exomoon binaries,  $e = 0.01$  and  $e = 0.001$ , are discussed by Heller & Armstrong (2014). Heller et al. (2014) concluded that satellites of  $0.1 - 0.5M_{\oplus}$  are potentially habitable, can form within the circumplanetary debris and gas disk or via capture from a binary, and are detectable with current technology. Studies of specific hypothetical exomoon systems include HD 23079 (Cuntz et al., 2013), and Kepler–62 (Sasaki & Barnes, 2014).

During planet formation, terrestrial-sized planets with lunar-sized companions may be ejected into interstellar space, with the two still bound (§11.4.4). The companion provides a further source of heating for the planet from tidal dissipation of orbital and spin angular momentum, typically exceeding the present radiogenic heating of the Earth for up to the first few hundred Myr, perhaps providing its own habitable zone (Debes & Sigurdsson, 2007).

Assuming that a heat flux between  $\sim 0.04 - 2 \text{ W m}^{-2}$  drives plate tectonics without unacceptable volcanism, the epochs at which habitability is possible can then be estimated. Thus around stars of  $M_{\star} = 0.2M_{\odot}$ , planets of  $M_{\text{p}} = 1 - 10M_{\oplus}$  can experience acceptable levels of tidal heating for  $> 10 - 100$  Gyr over a wide range of initial eccentricities,  $e_0 \sim 0.2 - 0.8$ .

**Tidal heating of exomoons** The habitability of exoplanet satellites (box, page 627) will also be affected by tidal heating (Williams et al., 1997; Scharf, 2006, 2008). As well as tidal dissipation due to eccentricity damping, tidal heating can occur as a result of other resonances, such as mean motion resonances (as in the Laplacian resonance of Io, Europa, and Ganymede), and spin–orbit

libration (Wisdom, 2004) or obliquity tides (Tyler, 2011; Chen & Nimmo, 2011) as have been considered (but excluded) for the case of Enceladus, or even global liquid ocean tides (Chen & Nimmo, 2011).

Scharf (2008) concluded, for example, that a Mars-sized ( $0.1M_{\oplus}$ ) moon with a terrestrial-like atmosphere and Europa-like  $a$  and  $e$  around any of the known exoplanets capable of retaining satellites, could readily attain a tidally-driven habitable surface temperature (i.e.  $273 \text{ K} < T < 373 \text{ K}$ ) over several Gyr, if the necessary driving conditions (e.g. orbital resonance) are maintained.

Tidal heating of ejected planet–satellite pairs has also been considered (§11.4.4).

### 11.7.3 Habitability criteria

Not all planets within some specified habitable zone (§11.7.1) are necessarily likely to be habitable. Many factors have been considered that are likely to influence habitability, and therefore influence search prospects (Horner & Jones, 2010; Kaltenecker et al., 2010a; Kaltenecker, 2017).

**Stellar mass and spectral type** The mass of a star on the main sequence determines its luminosity, spectral energy distribution, and lifetime. Habitability is likely to be governed by the range of stellar types for which life has enough time to evolve, i.e. stars not more massive than spectral type A. Even F stars have somewhat narrower continuously habitable zones because of their more rapid evolution. In contrast, stars less massive than the Sun have longer lifetimes, and planets or moons can spend more time within the habitable zone before they transition inside the expanding inner edge (Rushby et al., 2013).

Late K and M dwarfs may not be the most favourable to host habitable planets, in part because the planets can become trapped in synchronous rotation due to tidal damping (also resulting in relatively weak intrinsic planetary magnetic moments), and in part because of the high incidence of coronal mass ejections, together resulting in little protection from high-energy particle radiation (Khodachenko et al., 2007b; Lammer et al., 2007; Kay et al., 2016). They may also be strong intermittent emitters of ultraviolet radiation during flares (Bucino et al., 2007). A further restriction may emerge from detailed formation studies: even if planets are formed at suitable orbital separations, they may be underabundant in required volatiles (Lissauer, 2007). In a detailed evaluation of the advantages and disadvantages of M stars as targets in searches for terrestrial-zone habitable planets, Scalo et al. (2007) reasoned that their planets *‘must survive a number of early trials in order to enjoy their many Gyr of dynamical stability.’*

As a result of such considerations, Kasting et al. (1993) considered that mid- to early-K and G stars may

be optimal for the development of life, while others have considered that K dwarfs are particularly favourable when compared with G or M dwarfs (Heller & Armstrong, 2014; Cuntz & Guinan, 2016).

**Stellar metallicity** Habitability is further influenced, in spatial and temporal extent, by the host star metallicity through various effects, including effects of lifetime and impact shielding (Wetherill, 1994; Gonzalez, 1999b; Waltham, 2011; Young et al., 2012; Gallet et al., 2017b).

**Stellar ultraviolet irradiation** Ultraviolet radiation, in particular at 200–300 nm, is damaging to most terrestrial biological systems, inhibiting photosynthesis, destroying DNA, and damaging a wide variety of proteins and lipids (e.g. Sato et al., 2014). Ultraviolet radiation is nevertheless believed to have been an important energy source on the primitive Earth, underlying the synthesis of many biochemical compounds and, therefore, essential for several biogenic processes. In the Archean Earth, without its atmospheric protection, radiation spanning the UVB (280–315 nm) and UVC (190–280 nm) would probably have reached Earth's surface with little attenuation (Sagan, 1973b).

These considerations have been used to define the boundaries of a plausible *ultraviolet habitable zone* as a function of stellar spectral type, constraining inner limits determined by the levels tolerable by DNA, and outer limits characterised by the minimum levels needed in biogenic processes (e.g. Buccino et al., 2002, 2004, 2006; Rugheimer et al., 2015b; Oishi & Kamaya, 2016b; Sengupta, 2016a). Constraints for K and M dwarfs have also been obtained from HST (France et al., 2014).

M dwarfs, generally favourable for studies of the habitable-zone, remain very active and emit significant X-ray and ultraviolet radiation during their first Gy (Scalo et al., 2007). They may continue to emit significant ultraviolet radiation during flares (Buccino et al., 2007), affecting the detection of signatures of habitability (Rugheimer et al., 2015a), and contributing to atmospheric erosion (Airapetian et al., 2017), while the quiescent ultraviolet flux from evolved M dwarfs may be too weak for the synthesis of some essential biochemical compounds (Guo et al., 2010).

The activity-driven extreme ultraviolet flux of G stars (such as the Sun) falls off much more rapidly with increasing age, but their quiescent ultraviolet flux is enhanced with respect to K and M dwarfs. K dwarfs may therefore offer a suitable compromise between moderate initial and long-term high-energy radiation (Cockell, 1999; Heller & Armstrong, 2014).

**Super-flares** The phenomena of stellar flares and super-flares are described in Section 8.10.6. It is possible that super-flares are not expected in the case of the Sun, specifically if they are associated with magnetic re-

connection between the fields of the star and a close-in Jovian planet with sufficient magnetic dipole strength.

In any case, solar observations have not been undertaken for sufficiently long periods to directly document their existence (Usoskin, 2017). A super-flare on the Sun with energy  $10^{27}$  J that occurred in 775 CE has been posited (Melott & Thomas, 2012; Usoskin et al., 2013; Mekhaldi et al., 2015), but questioned (Miyake et al., 2012; Cliver et al., 2014; Neuhäuser & Neuhäuser, 2015), with another dating from 993 CE similarly associated (Miyake et al., 2013; Mekhaldi et al., 2015), and similarly questioned (Stephenson, 2015). The 1859 Carrington flare (Carrington, 1859; Cliver & Svalgaard, 2004) is one of the most powerful solar storms documented, with a total energy  $\sim 5 \times 10^{25}$  J (Cliver & Dietrich, 2013).

Other events, and associated effects on O<sub>3</sub> depletion, surface air temperatures, and the biosphere more generally, are detailed by Lingam & Loeb (2017d). Indeed, with some caveats, Lingam & Loeb (2017d) conclude that the risk posed by super-flares has not been sufficiently appreciated, and that Earth might experience a super-flare event in the next 1000 yr, leading to substantial economic and technological losses.

**Planet mass and plate tectonics** Within the  $\sim 1$  au habitability zone, Earth- (or super-Earth) planets can be considered as those with masses between  $0.5\text{--}10 M_{\oplus}$  or, equivalently, radii between  $0.8\text{--}2.2 R_{\oplus}$ . Planets below this mass are likely to lose their life-supporting atmospheres because of their low gravity, while more massive systems are unlikely to be habitable because they can attract a H–He atmosphere and become gas giants (Huang, 1960). Similar upper limits on planet radius are found when including considerations of ice layers in putative oceans (Alibert, 2015), while more statistical-based considerations are given by (Simpson, 2016).

The existence of mantle convection and plate tectonics (cf. §12.3.5) has been variously considered for specific exoplanet (or exomoon) masses and compositions (e.g. Ćirković, 2004a; Parnell, 2005; O'Neill & Lenardic, 2007; Valencia et al., 2007a; Kite et al., 2009; Valencia & O'Connell, 2009; Kaltenecker & Sasselov, 2010; Korenaga, 2010; Ruiz, 2011; Stamenković et al., 2011; van Summeren et al., 2011; van Heck & Tackley, 2011; Edson et al., 2012; Foley et al., 2012; Korenaga, 2012; Lenardic & Crowley, 2012; O'Rourke & Korenaga, 2012; Stamenković et al., 2012; Bercovici & Ricard, 2013; Stein et al., 2013; Jura et al., 2014; Miyagoshi et al., 2014; Noack & Breuer, 2014; Foley, 2015; Miyagoshi et al., 2015; Weller et al., 2015; Forgan & Dobos, 2016; Lourenço et al., 2016; Stamenković & Seager, 2016; Weller & Lenardic, 2016; Miyagoshi et al., 2017).

Arguments run, broadly, that on low-mass planets in which plate tectonics is inhibited, CO<sub>2</sub> would be progressively captured on the sea floor, leading to a global snowball state. In contrast, planets with masses several



times that of Earth develop high pressures in their mantle, and the resulting enhanced viscosities make plate tectonics less likely (Noack & Breuer, 2014). Moreover, a *stagnant lid* forms at the core–mantle boundary; this allows only a reduced heat flow from the core, and thereby also inhibits tectonics (Stamenković et al., 2011; Noack et al., 2017a; Tosi et al., 2017).

Different studies have reported different results, some demonstrating the inevitability of plate tectonics on super-Earths (e.g. Valencia et al., 2007a), and others arguing against it (e.g. O’Neill & Lenardic, 2007).

For super-Earths, initially heated by giant impacts at the time of formation, mantle convection occurs as a layered convection for the first 1–10 Gyr, then changes into a whole layer convection. The long duration of the transient stage suggests that mantle convection currently occurs as a temporal layered convection in many super-Earths (Miyagoshi et al., 2017).

The use of spectroscopic proxies in the atmospheric pollution of white dwarfs, perhaps providing evidence for plate tectonics, is considered in Section 8.9.5.

Following Lenardic & Crowley (2012), for a planet to have plate tectonics, its upper strong rock layer, the lithosphere, must experience localised plastic failure in response to stresses generated by thermal convection in the planet’s mantle. Below this yield stress, the mantle rheology remains on a (temperature-dependent) viscous branch. If the yield stress is reached, the lithosphere undergoes plastic failure which allows for the generation of localised zones of weakness that mimic plate boundaries. In the absence of such weak zones, and with highly temperature dependent viscosity, the upper cold boundary layer would resist convective motions, the lithosphere would remain stagnant, and a single plate (‘stagnant lid’) planet would result. Lenardic & Crowley (2012) has argued that different solutions, all viable and stable, can result from identical models and parameter values, and that the question of whether extrasolar terrestrial planets have plate tectonics is unanswerable, and will remain so until their temporal evolution can be constrained.

This basic idea has been employed by numerous models of coupled mantle convection and tectonics applied to solar system planets (Moresi & Solomatov, 1998; Bercovici, 2003), often reaching different conclusions.

Plate tectonics may peak between 1–5 $M_{\oplus}$  (Noack & Breuer, 2014), depending on composition and primordial heat reservoir. A tentative conclusion is that planets with  $M_p \sim 1 - 2M_{\oplus}$  may be favoured from a tectonic point of view, relative to planets of somewhat lower or higher mass. Planets slightly more massive than Earth may also be somewhat more favourable because their thicker atmospheres would provide improved shielding against high-energy irradiation, improved balancing of day-night temperature contrasts, and improved global distribution of water (Heller & Armstrong, 2014).

Assuming that the presence of a C-cycle is a necessary condition for long-term habitability, Alibert (2014) used internal structure models, using a 5-layer model (core, inner mantle, outer mantle, ocean, and atmosphere), for different masses and composition of the planets (in particular, the Fe/Si ratio of the planet) to compute the maximum radius a planet can have to fulfil two constraints: surface conditions compatible with the existence of liquid water, and no ice layer at the bottom of a pu-

tative global ocean. Above a given radius, these two constraints cannot be met. They argue that for planets in the super-Earth mass range (1–12 $M_{\oplus}$ ), the maximum radius that a planet can have, for an Earth-like composition, varies between 1.7–2.2 $R_{\oplus}$ .

**Volcanic outgassing** The N<sub>2</sub>-CO<sub>2</sub>-H<sub>2</sub>O habitable zone extends out to ~1.7 au in the solar system, beyond which CO<sub>2</sub> condensation and scattering outstrips its greenhouse capacity. Ramirez & Kaltenegger (2017) showed that volcanic outgassing of H<sub>2</sub> can extend the outer edge to 2.4 au, while the inner edge moves out by only 0.1–4%. This wider *volcanic-H<sub>2</sub> habitable zone* can be sustained as long as the H<sub>2</sub> output offsets its atmospheric escape.

**Photosynthesis** The Sun emits most of its light between 400–700 nm, which is the part of the spectrum visible to the human eye, and over which plants and others perform oxygenic *photosynthesis* (§11.8.5). Cuntz et al. (2012) described the ‘photosynthesis-sustaining habitable zone’, determined by the limits of biological productivity on the planet’s surface.

Without implying that this process is a pre-condition for life, it is possible that around M dwarfs, with  $M_{\star} < 0.6M_{\odot}$ , specific life forms might not have the capacity to harvest energy for survival because their stars have radiation maxima in the infrared. However, cyanobacteria are known which exploit longer wavelength radiation (Miller et al., 2005; Chen & Blankenship, 2011), such that photosynthesis may still occur on exoplanets in the habitable zone of M dwarfs (Kiang et al., 2007b,a; Stomp et al., 2007; Raven, 2007; O’Malley-James et al., 2012; Gale & Wandel, 2017). Other forms, e.g. chlorinic photosynthesis, and their associated spectral signatures, have been suggested (Haas, 2010), as have other evolutionary drivers (e.g. Brown et al., 2014).

**Atmospheric composition** Considerable speculation is possible in terms of the dependency of habitability on atmospheric composition. For example, enhanced atmospheric oxygen might allow a larger range of metabolic networks (Bernier et al., 2007), while variations in the atmospheric oxygen concentration may influence the macroevolutionary history of organismal size (Harrison et al., 2010; Payne et al., 2011). A range of oxygen partial pressures would appear to be compatible with an ecosystem broadly similar to Earth’s.

**General circulation models** Many insights into habitability are being gained from the kind of detailed atmospheric ‘general circulation models’ introduced in Section 11.4.2.

**Liquid water over geological time scales** Conventional definitions of habitability require abundant liquid surface water to exist continuously over geological timescales. Water in each of its thermodynamic phases interacts with solar and thermal radiation and is the cause of strong climatic feedbacks. Wolf et al. (2017) used the NCAR Community Atmosphere Model to study the evolution of climate for an Earth-like planet at constant CO<sub>2</sub>, under a wide range of stellar fluxes from F-, G-, and K-dwarf main sequence stars. Around each star they found four stable climate states defined by mutually exclusive global mean surface temperatures: snowball ( $T_s \leq 235$  K), waterbelt ( $T_s =$

**The anthropic principle:** The Universe that we observe is compatible with our own existence. Variations of this superficially self-evident statement, presented in different forms as the *anthropic [cosmological] principle*, have been extensively analysed by physicists, biologists, and philosophers for many years. Early examples of qualitative inference about the Universe attributable to the existence of human observers include Boltzmann (1895), who argued that we are confronted by improbable disequilibrium states of the cosmos because the more probable equilibrium state would contain no observers, while A.R. Wallace (1904, pp256–57) wrote that ‘Such a vast and complex Universe... may have been absolutely required... in order to produce a world that should be precisely adapted in every detail for the orderly development of life culminating in man’.

The term was first used by Carter (1974), following his investigation into the causal links between various fundamental constants (including particle masses, the electron charge, and the strong and weak interaction coupling constants) and a number of physical and astronomical phenomena (Carter, 2007, being a transcript of a preprint issued in 1967). He noted some remarkable relations between them (op. cit., eqns 6–8). Carter’s *weak anthropic principle* then argues that ‘our location in the Universe is necessarily privileged to the extent of being compatible with our existence as observers’.

Carter’s *strong anthropic principle* goes further, asserting that ‘the Universe (and hence the fundamental parameters on which it depends) must be such as to admit the creation of observers within it at some stage’. This proposition rests on the precise fine tuning of numerous physical constants which appears necessary for the stable existence of nuclei, atoms, and stars, in turn allowing the Universe to progress through numerous critical stages from baryogenesis, through the formation of galaxies, stars and planets, to the appearance of life and consciousness.

Barrow & Tipler (1986) undertook a comprehensive study, and detailed a substantial body of anthropic coincidences and constraints. Their *modified form of the weak anthropic principle* holds that ‘The observed values of all physical and cosmological quantities are not equally probable but they take on values restricted by the requirement that there exist sites where carbon-based life can evolve and by the requirement that the Universe be old enough for it to have already done so’, while their *strong anthropic principle* asserts that ‘The Universe must have those properties which allow life to develop within it at some stage in its history’. Yet more speculative formulations, including Wheeler’s ‘participatory anthropic principle’ (essentially appealing to quantum mechanics to conclude that observers are necessary to bring the Universe into being), and Tipler’s ‘final anthropic principle’ (that intelligent information-processing must come into existence in the Universe and, once it comes into existence, it will never die out), have been less widely embraced.

In an example of its early ‘application’, Dirac (1937) had argued that the mysterious ‘large-number coincidence’ between the dimensionless age of the Universe  $T_U \sim 10^{10}$  yr expressed in atomic units  $\tau = e^2/m_e c^3$ , viz.  $T = T_U/\tau \sim 10^{40}$ , and the inverse gravitational coupling constant  $\alpha_G^{-1} = hc/Gm_p^2 \sim 10^{40}$ , suggested that the coincidence is exact, with the equality  $T = \alpha_G^{-1}$  in turn implying that some fundamental ‘constants’ must vary with time (García-Berro et al., 2007). Dicke (1961) countered with anthropic-type arguments that such a conclusion is unwarranted given that life is only likely to develop at an epoch, dictated by stellar main sequence lifetimes, providing both heavy elements from stellar evolution, along with suitable planet-hosting stars. As described by Barrow & Tipler (1986, pp250–253), Hoyle may have invoked anthropic reasoning when deducing, from the prevalence of  $^{12}\text{C}$ -based life forms, that there must be an undiscovered resonance in the  $^{12}\text{C}$  nucleus facilitating its synthesis in stellar interiors, predicted and subsequently confirmed to be of energy 7.6 MeV (Hoyle et al., 1953; Hoyle, 1954; Burbidge et al., 1957; Livio et al., 1989). Rees (2000) suggested that anthropic reasoning is needed to explain the values of six constants required for life to exist (selecting three which control the fundamental interactions of physics, and three that determine the expansion of the Universe and the growth of structures in it). With more of a biological emphasis, Carter (1983) argued that ‘The evidence suggests the evolutionary chain included at least one but probably not more than two links which were highly improbable (a priori) in the time available’.

In cosmology, the anthropic principle has become more widely debated as a result of three developments (Ellis, 2011): (a) the pressing problem of the magnitude of the cosmological constant (Weinberg, 1987); (b) chaotic inflation as a means of providing many disconnected expanding universe domains with different physical constants in each (Linde, 1986); and (c) the development of string theory in which the variation of effective constants might naturally arise (Susskind, 2003).

235–250 K), temperate ( $T_s = 275$ –315 K), and moist greenhouse ( $T_s \geq 330$  K). Each is separated by abrupt climatic transitions. Waterbelt, temperate, and cooler moist greenhouse climates can maintain open-ocean against both sea ice albedo and hydrogen escape processes respectively, and thus constitute habitable worlds. They consider the warmest possible habitable planet as having  $T_s = 355$  K, at which point diffusion limited water-loss could remove an Earth ocean in 1 Gyr. Without long time scale regulation of non-condensable greenhouse species at Earth-like temperatures and pressures, such as  $\text{CO}_2$ , habitability can be maintained for 2.2, 2.4, and 4.7 Gyr around F-, G-, and K-dwarf stars, due to main sequence brightening.

**Unstable climates in the outer regions** For Earth-like planets, climate stability can be tied to the carbon–silicate cycle (§12.3.5). Essentially, atmospheric  $\text{CO}_2$  dissolves into rainwater as carbonic acid, is delivered to the surface, reacts with the rock,

and is eventually carried to the oceans, where it can be recycled into the mantle via subduction. On planets with vascular land plants, the direct dependence of weathering on the  $\text{CO}_2$  partial pressure is weakened by plant activity affecting carbon levels in the soil (Schwartzman & Volk, 1989; Berner, 1994; Pierrehumbert, 2010). However, on planets lacking land plants, the carbon cycle is more strongly-coupled and acts as a negative feedback on the planet’s surface temperature; increased temperatures or  $\text{CO}_2$  partial pressure surpluses lead to increased weathering and  $\text{CO}_2$  sequestration, while a deficit reduces weathering, allowing volcanic outgassing to replenish  $\text{CO}_2$ , and the climate tends toward an equilibrium point. At low insolation, the equilibrium point may be cold enough for total glaciation (Hoffman et al., 1998; Pierrehumbert, 2005; Menou, 2015), called a ‘snowball’ state. Budyko (1969) showed that such states can exist at the same insolation and  $\text{CO}_2$  partial pressures as temperate climates, and therefore require either high insolation or signif-

icant greenhouse gases for deglaciation. In this scenario of a snowball state triggered by weathering, weathering ceases in the absence of liquid water, implying that no weathering equilibrium can be reached. Volcanic outgassing continues, and at a certain point the CO<sub>2</sub> partial pressure will be high enough for the ice to melt, resulting briefly in warm wet conditions, followed by rapid weathering and cooling. Thus, on geological timescales, the climate may cycle between long snowball events and brief warm wet periods (Menou, 2015). Both 1d (Menou, 2015) and 3d (Paradise & Menou, 2017) energy-balanced climate models of Earth-like planets at varying orbital distances throughout the habitable zone show that these oscillating ‘climate cycles’ should dominate much of the outer region. Less optimistic CO<sub>2</sub>-driven ‘escape’ from a snowball state was found by Turbet et al. (2017).

**Dependence on planetary rotation rate** Noda et al. (2017) used an atmospheric general circulation model, with simplified hydrological and radiative processes, to investigate the effect of planetary rotation rate on a planetary surface covered with a swamp ocean. The value of planetary rotation rate was varied from zero to the Earth’s, while other parameters such as planetary radius, mean molecular weight and total mass of atmospheric dry components, and solar constant are set to the present Earth’s values. Results show that the atmosphere reaches statistically equilibrium states for all runs, with none exemplifying the runaway greenhouse state. The circulation patterns obtained are classified into four types: type I dominated by a day-night thermally direct circulation, type II characterised by a zonal wave number one resonant Rossby wave over a meridionally broad westerly jet on the equator, type III by a long time scale north–south asymmetric variation, and type IV by a pair of mid-latitude westerly jets. With the increase of planetary rotation rate, the circulation evolves from type I to type II and then to type III gradually and smoothly, whereas the change from type III to type IV is abrupt and discontinuous. Despite substantial changes in circulation, the net energy transport from the day-side to the night-side remains almost insensitive to planetary rotation rate, although the partition into dry static energy and latent heat energy transports changes.

**Tides** Tidal effects are often cited as a facilitator for the development of life on Earth. Specifically, the early (3.9 Ga) impact that produced the Moon, along with fast terrestrial rotation, subjected coastal areas to rapid tidal flooding (dilution) and drying (concentration), with a likely periodicity in the range of 2–6 h, and could have provided a driving force for cyclic replication of early biomolecules including nucleic acids. This existence of rapid tidal cycling, and an associated *tidal chain reaction*, may have amplified template-directed polymer assembly at the origins of life on Earth (Lathe, 2004) and Lathe (2005).

**Magnetic shielding** Surface life is assumed to require some level of shielding, against energetic particles from the host star, and against high-energy cosmic rays (Baumstark-Khan & Facius, 2002). Excessive particle flux could destroy molecules relevant for life, or it could strip the planet’s atmosphere (Luhmann et al., 1992).

Protection can be partly provided by the atmosphere, and more so by a global magnetic field, whether

intrinsic as on Earth, or extrinsic as may be the case on moons (Heller & Zuluaga, 2013; Atri et al., 2013; See et al., 2014). At the same time, while a giant planet’s magnetosphere can shield a moon against cosmic rays and stellar radiation, it may itself induce a bombardment of the moon with ionised particles trapped in the planet’s radiation belt, as in the case of Jupiter (Fischer et al., 1996).

To sustain an intrinsic magnetic field strong enough for protection over billions of years, a terrestrial world is assumed to require a liquid, rotating, and convective core, as on Earth (box, page 663). Less massive planets or moons will have weaker, short-lived magnetic shields. Williams et al. (1997) estimated a minimum mass of  $0.07M_{\oplus}$  for a world under solar irradiation to retain atmospheric oxygen and nitrogen over 4.5 Gyr. Beyond that, the dipole component of the magnetic moment  $\mathcal{M}$  depends on the core radius  $r_0$ , rotation frequency  $\Omega$ , and the thickness  $D$  of the core rotating shell where convection occurs via  $\mathcal{M} \propto r_0^3 D^{5/9} \Omega^{7/6}$  (Olson & Christensen, 2006; López-Morales et al., 2011). This in turn implies that tidally-locked planets and moons in wide orbits may have weak magnetic shielding.

**Galactic cosmic rays** As already noted, shielding by a planetary magnetic field is important in considering the effects of Galactic cosmic rays (X-rays,  $\gamma$ -rays, and heavy ions). Studies have been made of fluxes, shielding, and effects of ionisation as a function of planet type, including effects on atmospheric chemistry and composition, for example levels of O<sub>3</sub>, NO<sub>x</sub>, and HNO<sub>3</sub> (e.g. Grießmeier et al., 2005b; Grenfell et al., 2007a; Cohen et al., 2012; Atri et al., 2013; Rimmer & Helling, 2013; Rimmer et al., 2014; Grießmeier et al., 2015, 2016; Tabataba-Vakili et al., 2016). An international consortium, STARLIFE, is investigating the response of different biological model systems to different types of ionising radiation (Moeller et al., 2017).

**Formation and orbits** In the solar system, planet rotation rates (§12.4.5) and obliquities (§12.4.6) appear to have arisen from random events involved in its formation, with Earth’s Moon stabilising its obliquity (§12.3.3), and Jupiter (possibly) acting as a deflecting ‘sentinel’ (§12.2.2). The extent to which these effects influence habitability is unknown (e.g. Heller & Armstrong, 2014).

For example, studies have indicated that Earth’s rotation axis could be stable without the presence of a massive satellite (Lissauer et al., 2012a), and that such stability is perhaps not desirable (Spiegel et al., 2009a; Armstrong et al., 2014b). In the latter case, planets with a large tilt can break the ice-albedo feedback at locations further from the star, keeping the planet from entering the ‘snowball Earth’ stage (Williams & Kasting, 1997), and systems with varying tilts or larger Milankovitch-type cycles (footnote, page 681) could provide slow but steady changes in ecosystems that may be conducive to the evolution of life.

From the lunar forming impact (§12.3.3) to the Late Heavy Bombardment (box, page 669), the impact history of the Earth has influenced its surface environment, the delivery of organic molecules and volatiles (§12.3.4), and its spin-orbit evolution (§12.3.3). Heller & Armstrong (2014) have discussed how events like the Late Heavy Bombardment, itself sensitive to the particular dynamical conditions (§12.6), may be important in shaping habitability more generally.

The presence of an eccentric Jupiter may reduce the water content of planets formed inward of it (Raymond et al., 2007a). In contrast, very water-rich planets may form in the wake of migrating Jupiters (Raymond et al., 2005a, 2006b; Mandell et al., 2007).

**The anthropic principle** Many other conditions have been hypothesised as necessary or desirable for the development of life, largely based on the single life form known in the Universe, namely that on the Earth. Hypothetical conditions rapidly become tied to the more philosophical discussions of the *anthropic principle* which, in its various forms, broadly states that the physical Universe must be compatible with the conscious life that observes it (box, page 630).

A comprehensive if somewhat dated entry into the extensive literature on the anthropic principle is given by Balashov (1991), with a recent perspective given by Ellis (2011). Opinions today (summarised in Carr, 2007) range from those who consider it as a key foundation for cosmological inference, to those like Penrose (1989, Chapter 10) who consider that *‘It tends to be invoked by theorists whenever they do not have a good enough theory to explain the observed facts’*.

The subject remains controversial, with no consensus as to whether the ‘principle’ (in its various forms) offers explanatory and predictive power, or is simply a statement of selection effects, speculation, or tautology.

**Our existence around a G dwarf** M dwarfs are more abundant than G dwarfs, so our position as observers on a planet orbiting a G dwarf can be considered from an anthropic perspective, in turn questioning the suitability of other stellar types for supporting life. Haqq-Misra et al. (2018a) analyse this problem through Bayesian inference to demonstrate that our existence around a G dwarf might be a slight statistical anomaly, while mid G- to early K-dwarfs stars still appear to be the most likely place for observers like ourselves. This may suggest, in turn, that observers with similar cognitive capabilities are most likely to be found at the present time and place, rather than in the future or around much smaller stars.

**Superhabitability** Heller & Armstrong (2014) introduced the concept of *superhabitability* to describe planets (or moons) that may offer an even more benign or enhanced environment for life than Earth’s. In addition to the various criteria possibly essential for life discussed in the foregoing, they suggest that superhabitability might be influenced by various other factors.

Amongst these, they suggest larger total surface and habitable areas, and some optimum land-to-ocean fraction, with shallow waters on Earth having a higher biodiversity than the deep oceans (Gray, 1997), and perhaps with drier planets having wider stellar habitable zones (Abe et al., 2011).

Systems with more than one habitable zone terrestrial planet or exomoon may open the possibility of triggered material exchange through impacts of comets or asteroids, and the mutual fertilisation among multiple habitable worlds (viz. panspermia, §11.8.3).

Terrestrial worlds located more towards the centre of the habitable zone than Earth may be favoured, while older systems might be more habitable, by appeal to Earth’s steady increase in biodiversity with time (Mayhew et al., 2012).

Taken together with the considerations on stellar mass, luminosity, spectral energy distribution, lifetime, and ultraviolet irradiation, Heller & Armstrong (2014) suggest that K dwarfs may be particularly favourable habitable hosts.

In contrast to the tenets of the ‘rare Earth hypothesis’ of Ward & Brownlee (2000), in which the emergence of life on Earth required an unlikely interplay of conditions such that complex life would be unlikely elsewhere in the Universe, they suggest that Earth may, instead, be only a ‘marginally habitable’ world. A variety of processes could make environmental conditions on other planets even more favourable to life.

#### 11.7.4 Earth-like planets in the habitable zone

**Eta Earth** The term *Eta Earth*, or  $\eta_{\oplus}$ , was introduced to describe the (as yet unknown) fraction of stars that host an Earth-like planet. This can be interpreted in different ways, for example, as the fraction of *Sun-like* stars with Earth-like planets *in their habitable zones*. Even so, all these qualifiers (Sun-like, Earth-like, and habitable zone) are imprecise and open to interpretation.<sup>4</sup> Neither is there a consensus on the definition of ‘Earth-size’ (of particular relevance to transit measurements) or to

<sup>4</sup> Various descriptions of  $\eta_{\oplus}$  are in the literature, amongst them (Heller & Armstrong, 2014, Appendix A): the fraction of Sun-like stars that have at least one planet in the habitable zone (Lunine et al., 2008); the fraction of stars with Earth-mass planets in the habitable zone (Howard et al., 2009); the fraction of Earth-like planets with  $M_p \sin i = 0.5 - 2M_{\oplus}$  and  $P < 50$  d (Howard et al., 2010b); the fraction of Sun-like stars that have planets like Earth (Catanzarite & Shao, 2011b); the fraction of habitable planets for all Sun-like stars (Catanzarite & Shao, 2011b); the frequency of Earth-mass planets in the habitable zone (Wittenmyer et al., 2011b); the number of planets with  $0.1M_{\oplus} < M_p < 10M_{\oplus}$  in the 3 Gyr continuous habitable zone (Agol, 2011); the fraction of Sun-like stars with Earth-like planets in the habitable zone (O’Malley-James et al., 2013); the frequency of habitable planets orbiting M dwarfs (Bonfils et al., 2013a).

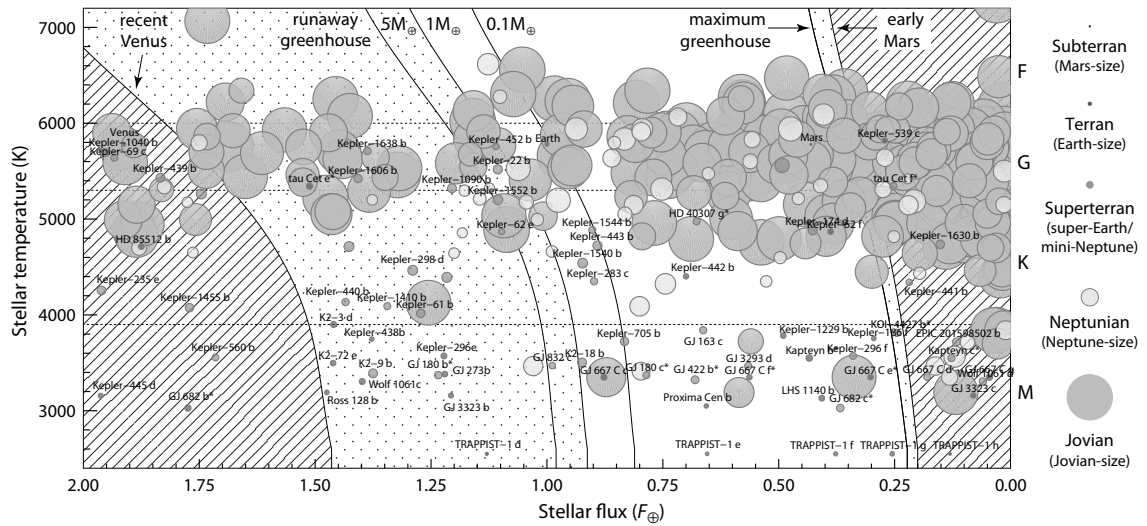


Figure 11.43: Planets in or near the habitable zone. The non-shaded region delineates the conservative habitable zone, the stippled area (for  $1M_{\oplus}$ ) denotes the 'optimistic' habitable zone (Kopparapu et al., 2014). Planets with  $M_p < 10M_{\oplus}$ , or  $R_p < 2.5R_{\oplus}$ , are labeled. Circle sizes are proportional to  $R_p$ , and estimated from a mass-radius relationship when not directly available. From the Planet Habitability Laboratory of the University of Puerto Rico ([phl.upr.edu/hec](http://phl.upr.edu/hec)), 2018 March, courtesy of Abel Méndez.

'Earth-mass'. For example (§1.6), Borucki et al. (2011b) adopted Earth-size as  $R_p < 1.25R_{\oplus}$ , while Kopparapu (2013) adopted  $0.5 - 1.4R_{\oplus}$ . These different definitions will influence estimates made in different ways.

With some of the most detailed estimates coming from the Kepler mission, other uncertainties in defining the occurrence rate of Earth-like planets include (Lissauer et al., 2014a; Traub, 2015): the extrapolation to smaller planet sizes, and to longer orbital periods, from those region where Kepler has its most statistically-reliable planet sample; extrapolations involving planets with and without substantial volatile envelopes, or a mix of formation histories; a robust consideration of false-positives, e.g. larger planets orbiting fainter stars projected closer to the host star on the plane of the sky (Fressin et al., 2013).

Current estimates span a fairly wide range, but values of order  $\eta_{\oplus} \sim 0.1$  seem plausible (§6.26.3). Estimates enter, amongst others, calculations of the effectiveness of space missions in detecting and characterising Earths (e.g. Léger et al., 2015).

**Earth Similarity Index** Schulze-Makuch et al. (2011) introduced a two-level classification scheme of exoplanet habitability. Their *Earth Similarity Index*, *ESI*, aims to quantify a planet's similarity to Earth. It is based on two quantities associated with the planet's interior (viz., its mean radius and bulk density), and two associated with its surface properties (viz., the escape velocity and surface temperature).

As implemented at the online Planetary Habitability Laboratory at the University of Puerto Rico (see

Table 1.4), the Earth Similarity Index is calculated as (Schulze-Makuch et al., 2011, eqn 1)

$$ESI = \prod_{i=1}^n \left( 1 - \left| \frac{x_i - x_{i_0}}{x_i + x_{i_0}} \right| \right)^{\frac{w_i}{n}}, \quad (11.45)$$

where  $x_i$  and  $x_{i_0}$  are properties of the planet and Earth respectively,  $w_i$  is the associated weighted exponent, and  $n$  is the total number of properties considered. The weights,  $w_i$ , are free parameters that can be chosen to emphasise certain characteristics. Since the quantities entering the index can be undefined or only poorly constrained at present, they may be estimates based on the best-available data, and will evolve with time.

Schulze-Makuch et al. (2011) also introduced a *Planetary Habitability Index*, *PHI*

$$PHI = (S \cdot E \cdot C \cdot L)^{1/4}, \quad (11.46)$$

designed to minimise bias in the search for life by taking into account that life might exist under more exotic conditions than on Earth. It is based on the geometric mean of separate variables related to the presence of a stable substrate ( $S$ , influenced by solid surfaces, atmosphere, and magnetosphere), available energy ( $E$ , influenced by light, heat, redox chemistry, and tidal flexing), appropriate chemistry ( $C$ , influenced by polymeric chemistry, probably based on  $C$ , but affected by the presence of  $N$ ,  $S$ ,  $P$ , and others), and the potential for holding a liquid solvent ( $L$ , either in the atmosphere, or on or beneath the surface). Such knowledge is typically beyond that currently available.

Table 11.9: The ‘conservative’ sample of potentially habitable exoplanets, listed by the Planet Habitability Laboratory of the University of Puerto Rico (ph1. upr. edu/hæc), as at 31 December 2017, flagged by discovery method (radial velocity/transit), and ordered by decreasing Earth Similarity Index, ESI (Equation 11.45). These are planets (perhaps) with a rocky composition ( $0.5R_{\oplus} < R_p \leq 1.5R_{\oplus}$ , or  $0.1M_{\oplus} < M_p \sin i \leq 5M_{\oplus}$ ), orbiting within their (conservative) habitable zone. When undetermined,  $M_p$  and  $R_p$  assume a rocky composition (the PHL compilation includes estimates for a pure Fe, rocky, and  $H_2O$  composition). Flux is the average received stellar flux in Earth units. The equilibrium temperature,  $T_{eq}$ , assumes a Bond albedo  $A_B = 0.3$ , while the actual surface temperatures will be larger, depending on (unknown) atmospheric composition. Larger ESI does not necessarily imply ‘more habitable’, since it does not consider all factors necessary for habitability (cf. §11.7.3).

Name	RV/ T	ST	$M_p$ ( $M_{\oplus}$ )	$R_p$ ( $R_{\oplus}$ )	Flux ( $S_{\oplus}$ )	$T_{eq}$ (K)	$P_{orb}$ (d)	$d$ (pc)	ESI	Discovery reference
Proxima Cen b	RV	M5	>1.3	1.1	0.70	227	11.2	1	0.87	Anglada-Escudé et al. (2016a)
TRAPPIST-1 e	T	M8	0.6	0.9	0.67	230	6.1	12	0.86	Gillon et al. (2017c)
GJ 667C c	RV	M1	>3.8	1.5	0.88	247	28.1	7	0.84	Bonfils et al. (2013a)
Kepler-442 b	T	K	2.3	1.3	0.70	233	112.3	236	0.84	Torres et al. (2015)
GJ 667C f	RV	M1	>2.7	1.4	0.56	221	39.0	7	0.77	Anglada-Escudé et al. (2013c)
Kepler-1229 b	T	M	2.7	1.4	0.49	213	86.8	236	0.73	Morton et al. (2016)
TRAPPIST-1 f	T	M8	0.7	1.0	0.38	200	9.2	12	0.68	Gillon et al. (2017c)
LHS 1140 b	T	M4	6.6	1.4	0.41	200	24.7	13	0.68	Dittmann et al. (2017b)
Kapteyn b	RV	M0	>4.8	1.6	0.43	205	48.6	4	0.67	Anglada-Escudé et al. (2014)
Kepler-62 f	T	K2	2.8	1.4	0.39	201	267.3	368	0.67	Borucki et al. (2013)
Kepler-186 f	T	M1	1.5	1.2	0.29	188	129.9	172	0.61	Quintana et al. (2014)
GJ 667C e	RV	M1	>2.7	1.4	0.30	189	62.2	7	0.60	Anglada-Escudé et al. (2013c)
TRAPPIST-1 g	T	M8	1.3	1.1	0.26	182	12.4	12	0.58	Gillon et al. (2017c)

Irwin et al. (2014) proposed a *Biological Complexity Index*, BCI, designed to provide a quantitative estimate of the relative probability that complex, macro-organismic life forms could have emerged on other worlds. The index ranks planets and moons by basic characteristics detectable with available technology. They inferred that 11 exoplanets known at the time (1.7%) have a BCI above that of Europa, implying that the evolution of complex life on other worlds is rare in frequency, but large in absolute number.

Other indices have been proposed, amongst them CD-HPF (Bora et al., 2016), and HabPREP (Cuntz & Guinan, 2016). Rodríguez-Mozos & Moya (2017) proposed a ‘Statistical-likelihood Exo-Planetary Habitability Index’ (SEPHI), as the geometric mean of four comparison criteria: telluric nature, atmospheric density, liquid water, and magnetic field. It can be estimated with seven physical characteristics: planet mass, radius, and orbital period, stellar mass, radius, and effective temperature, and the planetary system age.

Kashyap et al. (2017) introduced a ‘Mars Similarity Index’ (MSI), using the same physical parameters as ESI, to identify planets habitable to extreme forms of life.

A habitability index specifically for transiting planets, designed to prioritise follow-up of potentially habitable planets, accounts for degeneracy between eccentricity and albedo, exploits terrestrial mass–radius relationships, and down-selects large radius planets (Barnes et al., 2015c; Adams & Kane, 2016).

**Exoplanets in the habitable zone** Habitable zones have been modeled for many exoplanet systems (e.g. Jones & Sleep, 2010; Cantrell et al., 2013; Burke & Mc-

Cullough, 2014; Kane, 2014). Various efforts have been devoted to modeling the habitable zones of the Kepler systems (e.g. Haghighipour & Kirste, 2011; Kaltenegger & Sasselov, 2011; Gaidos, 2013; Pintr et al., 2014).

Effects of eccentricity on the planet’s equilibrium temperature (§6.24.2), and consequently on habitability, based on a mean thermal approximation (rather than the mean flux approximation) have been considered by Méndez & Rivera-Valentín (2017, their eqn 21).

As a result of these analyses, a number of planets have been reported to lie within their host star habitable zone (Figure 11.43). In the years following the first exoplanet discoveries, these were typically Jupiter-mass gas giants, and considered uninhabitable.

Since around 2013, and starting with the discoveries of GJ 667C c, e, and f (Bonfils et al., 2013a; Anglada-Escudé et al., 2013c) and Kepler-62 f (Borucki et al., 2013; Kaltenegger et al., 2013), an increasing number of habitable zone planets of terrestrial mass have been announced, rather equally distributed amongst radial velocity and transit discoveries. These include some very nearby systems, notably Proxima Cen, Kapteyn’s star, and GJ 667C, all within 10 pc.

In addition to specific candidates, the CELESTA database provides estimated habitable zones around 37 000 nearby stars (Chandler et al., 2016), of which 13 are single Jovian planet systems likely to support a stable Earth-mass planet in their habitable zone (Agnew et al., 2017). The ‘Habitable Zone Gallery’ (Table 1.4) provides information for systems with known planet orbits, including equilibrium temperatures and the fraction of the orbit spent within the habitable zone (Kane

& Gelino, 2012c). Bean et al. (2017) described a statistical comparative approach to determining H<sub>2</sub>O and CO<sub>2</sub> abundances to test the habitable zone hypothesis.

**Habitable Exoplanets Catalogue** An online compilation of potentially habitable planets is maintained via the University of Puerto Rico's Habitable Exoplanets Catalogue (HEC, Table 1.4). Their planet classification (Méndez, 2006) includes stellar spectral type (F, G, K, M), habitable zone location (classed as hot, warm, cold), and the planet's size (classified as miniterran, subterran, terran, superterran, jovian, or neptunian).

As of the end of 2017, HEC lists 13 planets with  $0.5R_{\oplus} < R_p \leq 1.5R_{\oplus}$ , or  $0.1M_{\oplus} < M_p \sin i \leq 5M_{\oplus}$ , and orbiting within the (conservative) habitable zone, i.e. those most likely to have a rocky composition with surface liquid water. These systems are shown in Figure 11.43 and listed in Table 11.9, where they are ordered by decreasing Earth Similarity Index, ESI (Equation 11.45). It lists a further 40 habitable zone planets with  $1.5R_{\oplus} < R_p \leq 2.5R_{\oplus}$ , or  $5M_{\oplus} < M_p \sin i \leq 10M_{\oplus}$ , i.e. those less likely to have a rocky composition or maintain surface liquid water.

Host star properties are being investigated for many candidates, e.g. from the Kepler light curves (Armstrong et al., 2016b), which can characterise rotation, activity, mass loss, and gyrochronology ages. Among the results, super-flares (§8.10.6) have been detected in Kepler-438.

**Other candidates** In addition to the candidates highlighted in the HEC, many other planets detected in radial velocity surveys, and the Kepler data, have been the subject of studies of their habitability. The literature is extensive, evolving, and still to some extent subjective. Some examples are given hereafter, without attempting completeness (see also Appendix C and D).

Doppler surveys have been successful in identifying possibly rocky planets ( $M \sin i < 10M_{\oplus}$ ) for a few bright (nearby) cool stars, where the habitable zone is close-in and reflex velocity amplitude is high. Other than those in the HEC, candidates include:  $\alpha$  Cen B (e.g. Forgan, 2012; Eggl et al., 2013a; Heller & Armstrong, 2014), GJ 163 c (Bonfils et al., 2013b), GJ 832 c (Wittenmyer et al., 2014c) HD 40307 g (Tuomi et al., 2013a; Brasser et al., 2014), and HIP 57050 (Haghighipour et al., 2010),

Of Kepler/K2 discoveries, some 10–20 with  $R_p \lesssim 2.0R_{\oplus}$  lie in or near the habitable zone. Other than those in the HEC, these include: Kepler-283 c, Kepler-296 e and f (Rowe et al., 2014), Kepler-438 b, Kepler-440 b, and Kepler-442 b (Torres et al., 2015), Kepler-452 b (Jenkins et al., 2015), and K2-3 d (Crossfield et al., 2015). A compilation from the Kepler Q1–Q17 data release, compiled by the Kepler Habitable Zone Working Group, lists 104 candidates within the optimistic habitable zone, of which 20 have  $R_p < 2R_{\oplus}$  (Kane et al., 2016a).

## 11.8 Life

On Earth, the definition, origin and evolution of life covers a vast range of biological, chemical, and geophysical research. Only a very few considerations most relevant to the ongoing topics of exoplanet research will be noted here. No generally-accepted evidence for life beyond Earth has been obtained to date.

### 11.8.1 Definition

Despite abundant empirical data, there is no generally accepted definition of life. In biology, life is considered to be a characteristic of organisms that display all, or most of, a set of phenomena including metabolism, growth, organisation, reproduction, adaptation, homeostasis (regulation), and response to stimuli.

Tsokolov (2009) analysed three approaches to defining life, and concluded that '*... all three are problematic in that they attempt to define life with undefined terms, confuse a description with a definition, or define life arbitrarily in terms of minimal living systems.*'

A widely-considered definition of life came through NASA's effort to create a 'working definition' for its exobiology and astrobiology programmes. The result defines life as '*a self-sustaining chemical system capable of Darwinian evolution*' (Joyce, 1994; Benner, 2010; Domagal-Goldman et al., 2016). This distinguishes life as an evolutionary process rather than by its chemistry, although the stipulation of *Darwinian* evolution may itself be overly specific (Cleland & Chyba, 2002).

Ćirković (2009) argued that the absence of a precise definition of life or intelligence does not deter biologists and cognitive scientists in their ongoing research, and that there is no reason why a different approach should be demanded in astrobiology and SETI studies: intuitive concepts of both are sufficiently developed to allow advancing research, while the history of science suggests that formal paradigms, including precise definitions, only occur at more mature disciplinary stages.

### 11.8.2 Abiogenesis

The term *abiogenesis* denotes the process by which life arises from non-living matter, and contrasts with *biogenesis*, which describes life forms arising from pre-existing life. Chemical, biological, and geophysical studies then aim to determine how pre-life chemical reactions gave rise to life on Earth.

Life on Earth is dependent on the specialised chemistry of carbon and water. Theories of abiogenesis seek to explain the origin and interactions of the various different families of chemicals (including lipids, carbohydrates, nitrogenous bases, phosphate groups, and amino acids) which form its building blocks.

Investigations include how self-replicating molecules came into existence, and how catalysis in chemical systems might have provided the precursor molecules necessary for self-replication (Brack et al., 2010). The complex organic molecules found across the solar system, and in interstellar space, may have provided the starting material for the development of life on Earth.

Five major stages of the origin of life have been distinguished, as summarised from the work of Eigen & Schuster (1982) by Domagal-Goldman et al. (2016, §3.3):

(i) the simplest organic building blocks were synthesised, starting from inorganic substrates; (ii) small organic molecules started self-organising, giving rise to larger more complex organic molecules; (iii) complex molecules interacted with each other, giving rise to the first reaction pathways, and the network of reactions among molecules in different reaction cycles began; (iv) macrostructures arose from the spontaneous aggregation of the simpler molecules, which led to compartmentalisation, and the chemical reaction cycles started to interact with the compartments; (v) the system was capable of being shifted from chemical equilibrium, maintaining homeostasis and undergoing evolution.

The processes are challenging: Howland (2000) cautioned that, given precursors such as amino acids and believing that a living organism would inevitably arise through self-assembly is '*...similar to a tornado descending on a junkyard and producing, by self-assembly, a jet airliner*'.

### 11.8.3 Development of life on Earth

The age of the Earth is about 4.54 Gyr. Study of zircons has found that liquid water must have existed as early as 4.40 Ga, very soon after its formation. The earliest undisputed evidence of (microbial) life on Earth dates from at least 3.5 Ga, but possibly earlier, after geological crust started to solidify following the molten Hadean Eon. Structurally similar to bacteria found near hydrothermal vents in the modern era, these findings have been taken to suggest that abiogenesis began near hydrothermal vents, detailed further below.

There is evidence that life on Earth was well established as early as 3.5 Ga (Schopf, 1993; Wacey et al., 2011), and possibly as early as 3.8 Gyr (Mojzsis et al., 1996). However, the ages of the most ancient fossils are difficult to determine and typically subject to debate. If life was thriving at these times, two possible scenarios emerge. The first is that life may have originated before or during the Late Heavy Bombardment, and survived this tumultuous period in the early history of Earth. This viewpoint is strengthened by evidence that indicates Earth may never have been fully sterilised during the Late Heavy Bombardment (Abramov & Mojzsis, 2009). Alternatively, just after the Late Heavy Bombardment, the conditions on primitive Earth were conducive to the rapid emergence of life (Oberbeck & Fogleman, 1989; Sleep et al., 2001).

Earth's early atmosphere is considered to have formed via volcanic degassing, providing N<sub>2</sub>, CO<sub>2</sub>, and (some) H<sub>2</sub>O. Impacts from comets and asteroids delivered a variety of organic volatiles to early Earth. More detailed chronologies of the development of life on Earth include a consideration of more problematic components such as phosphorus (e.g. Grenfell et al., 2010; Domagal-Goldman et al., 2016, §3.2).

**Habitability elsewhere in the solar system:** The following provides a summary of the current understanding of habitability elsewhere in the solar system. Further details, references, and descriptions of relevant spacecraft missions, are given by Domagal-Goldman et al. (2016, Chapter 6).

Due to their lack of liquid water, Earth's Moon and Mercury are not considered to be, or ever have been, habitable. The global cloud cover of Venus consists primarily of sulphuric acid, its surface and atmosphere are devoid of water, and its surface is around 740 K. Venus is not habitable today, but might have been earlier in its history.

The present Martian surface does not appear to be habitable. Surface water is scarce, although evidence suggests that liquid water was present at different stages of its history (§12.2.1). The thin atmosphere does not protect the surface from high doses of solar radiation. Conditions may have been more habitable in the relatively recent past (e.g. Ehlmann et al., 2016; Fairén et al., 2017; Vago et al., 2017).

The announcement of evidence for fossilised life within the Martian meteorite ALH84001 (McKay et al., 1996) was followed by the realisation that abiological processes could have created them. The meteorite is not therefore widely considered as proof of life beyond Earth (e.g. Bradley et al., 1997; Domagal-Goldman et al., 2016).

The Galileo mission to Europa provided compelling evidence for an ocean of liquid water beneath the surface ice layer (Kivelson et al., 2000), and therefore the most likely habitat for life on Europa.

Titan, Saturn's largest moon, is rich in organic molecules, and may be potentially habitable. Reactions with solar ultraviolet light and charged particles occur in its dense N<sub>2</sub>-CH<sub>4</sub> atmosphere, and produce a wide range of N-bearing organic molecules. Models of its formation and evolution predict that its interior consists of H<sub>2</sub>O-ice or CH<sub>4</sub>-clathrate layers several tens of km thick that overlies a water ocean several hundred km deep.

Enceladus has a south polar region shaped by tectonic forces, with plumes of gas and ice. Its interior may provide the requirements for life. Internal oceans may also exist in Neptune's moon Triton, and in Jupiter's Ganymede and Callisto, all with more complex layers of liquid and ice. Future missions will probe these icy moons for possible biosignatures (e.g. Chela-Flores, 2017).

Given that life arose on Earth sometime in the first few hundred Myr after the young planet had cooled to the point that it could support H<sub>2</sub>O-based organisms on its surface, the early emergence of life has been taken as evidence that the probability of abiogenesis is high, if starting from young Earth-like conditions. Finding a single case of life arising independently (elsewhere in the solar system, or on an exoplanet) would provide evidence that abiogenesis is not extremely rare in the Universe (Spiegel & Turner, 2012). Other attempts to model the temporal evolution of life on Earth and elsewhere have been made (e.g. McCabe & Lucas, 2010).

Some of the broader aspects of the development of atmospheric conditions on Earth are described in Section 12.3.8. In much greater detail, Smith & Morowitz (2016) explore the origin of life as a planetary process, arguing that the emergence of life on Earth was a neces-



sary cascade of non-equilibrium phase transitions that opened new channels for chemical energy flow.

**Hydrothermal vents** Conditions suitable for the origins of life have long been held to require liquid H<sub>2</sub>O, suitable chemistry ('CHNOPS', representing the six most important elements whose covalent combinations make up most biological molecules on Earth), and an energy source. Attention has moved away from the electrostatic discharge-type catalysis considered by Miller (1953), and is more focused on the dual additional advantages offered by high concentrations of organic compounds alongside environmental stability. These requirements are met on Earth around hydrothermal vents (e.g. Kelley et al., 2001; Früh-Green et al., 2003; Kelley et al., 2005; Arndt & Nisbet, 2012; Sojo et al., 2016; Cardoso & Cartwright, 2017; Russell & Nitschke, 2017). Such features may also exist on Jupiter's moon Europa, and Saturn's moon Enceladus (box, page 636).

**Black and white smokers** Hydrothermal vents are fissures in the planet's surface from which geothermally-heated water issues. In the deep ocean they typically form along the tectonically diverging mid-ocean ridges, such as the East Pacific Rise and the Mid-Atlantic Ridge, but they also occur in old regions of the oceanic crust away from spreading centres. The water issuing from them consists mostly of sea water drawn in through faults and porous sediments or volcanic strata. The surrounding areas are biologically productive, often hosting complex communities supported by the chemicals dissolved in the vent fluids. Chemosynthetic bacteria and archaea form the base of the food chain, supporting diverse organisms including extremophiles, including giant tube worms, clams, limpets and shrimp. Vents include the 'black smokers', chimney-like structures that emit black clouds with high levels of precipitable sulphides and first discovered in 1979 on the East Pacific Rise, and the generally cooler 'white smokers' containing Ba, Ca and Si.

Examples include the 40-m high 'Godzilla' vent structure, discovered in 1991 (Robigou et al., 1993) which collapsed in 1996; the 'Champagne vent' in the Marianas Trench Marine National Monument which produces almost pure liquid CO<sub>2</sub>, discovered in 2004 (Lupton et al., 2006); and the alkaline vents of the 'Lost City' field in the mid-Atlantic discovered during an NSF expedition in 2000 (Kelley et al., 2001), and the 'Strytan' field off the north coast of Iceland discovered in 2016. Lost City and Strytan provide rich ecosystems driven by the abiotic production of CH<sub>4</sub> and H<sub>2</sub> by serpentinisation (the hydration and metamorphic transformation of low-silica ultramafic rock).

Some 700 vent fields are listed in the InterRidge Global Database of Active Submarine Hydrothermal Vent Fields V3.4, hosted by the Institut de Physique du Globe de Paris, IGP (vents-data.interridge.org). A review covering the 70 known shallow-water (< 212 m) hydrothermal vents is given by Price & Giovannelli (2017).

**Extremophiles** Over the past few decades, microorganisms have been discovered in extreme environments on Earth (e.g. Cavicchioli, 2002; Horneck, 2006; Canganella & Wiegel, 2011; Martin & McMinn, 2018). These *extremophiles* are continually expanding knowledge of their tolerance limits and, even on Earth, the absolute physical and chemical limits of life are not known.

Microorganisms associated with measured extremes of physical and chemical parameters of habitability on Earth include (Domagal-Goldman et al., 2016, Table 4) high-temperature thermophiles, low-temperature psychrophiles, high-pressure barophiles, high-salinity halophiles, low-moisture xerophiles, alkaliphiles, acidophiles, and those particularly resistant to ultraviolet and ionising radiation. Dormant life (such as spores) can withstand even more extreme conditions.

**Microbial survival in space** Space is one of the most extreme environments where some life forms can still maintain their structure and potential to live, even though growth or multiplication has not been observed and is thought unlikely. The physical parameters that life must adapt to include low pressure, extreme temperatures, high levels of ultraviolet and particle radiation, and microgravity (Domagal-Goldman et al., 2016).

Their effects have been tested on different life forms since the 1930s: in simulation experiments (Olsson-Francis & Cockell, 2010); by missions in Earth orbit including NASA's Shuttle-borne Long Duration Exposure Facility (LDEF, 1984–90) and ESA's EXPOSE-E on the ISS between 2008–09 (Horneck & Zell, 2012); outside Earth's orbit during the Apollo programme (Horneck et al., 2010); and in dedicated experiments simulating exoplanet environments (Lage et al., 2012). Most experiments use bacteria, archaea, or viruses as biological models. Among the findings, spores of *Bacillus subtilis*, protected from solar ultraviolet radiation, survived the space environment for 6 years on LDEF.

**Panspermia** The *panspermia* hypothesis (box, page 638) holds that life exists throughout the Universe, and can be transferred between bodies by collisional processes.

Collisions are postulated to trap life forms that can survive the effects of space, such as extremophiles, which are then ejected from the parent body (Weber & Greenberg, 1985; Adams & Spiegel, 2005; Valtonen et al., 2009; Belbruno et al., 2012). The trapped life forms then lie dormant for an extended time before colliding with other planets or intermingling with protoplanetary disks, and dispersing throughout the Galaxy's habitable zone, ostensibly within a few Gyr. If met with suitable conditions on a new planet's surface, the bacteria become active and the process of evolution begins again.

Although panspermia offers no specific insight into *how* life originated, it offers prospects for increasing the probability of life becoming established. For example, Napier et al. (2007) propose that the totality of comets around Sun-like stars offers a more probable setting for the origin of life than any available on the early Earth (see also Martin & Livio, 2013b; Scharf & Cronin, 2016).

Because of the destructive effects of ultraviolet radiation and other harsh conditions of space (Horneck, 2008), proponents suggest that biological material must

**Panspermia:** The *panspermia hypothesis* (from the Greek 'pan' = all and 'sperma' = seed) holds that life exists throughout the Universe, and is distributed by meteoroids, asteroids, comets, and other small planetary system bodies. It postulates that life originated beyond Earth, and therefore addresses questions of where, rather than how, life originated. The related idea of *exogenesis* is a more limited hypothesis which proposes that life on Earth was transferred from elsewhere in the Universe, but makes no prediction about how widespread it is.

From the 5th century BC Greek philosopher Anaxagoras, the concept developed through the work of Berzelius (1834), Richter (1865), Kelvin (1871), and von Helmholtz (1879), and was further detailed by Arrhenius (1903), who coined the term. Hoyle & Wickramasinghe were influential proponents (Hoyle & Wickramasinghe, 1981; Wickramasinghe, 2003, 2011), further contending that life forms continue to enter Earth's atmosphere, and may be responsible for epidemic outbreaks and new diseases.

be encased in rock to survive the transfer process, a specific mechanism referred to as *lithopanspermia*. The required rock mass is often taken to be > 10 kg (Horneck, 1993; Benardini et al., 2003; Melosh, 2003), although improved transfer probabilities can be obtained for smaller mass (Napier, 2004). Damaged biological molecules might also seed new life through *necropanspermia* (Wesson, 2010). Seeding from icy ejecta has been termed *glaciopanspermia* (Houtkooper, 2011). Experimentally, Mastrapa et al. (2001) verified the survival of spores of *Bacillus subtilis* subjected to high acceleration simulating impact ejection from a Mars-like planet.

Worth et al. (2013) estimate that ~5% of impact remains from Earth have escaped the solar system, with a similar value obtained for Mars. The possibility of contamination of solar siblings by 'spores of life' from Earth could therefore make solar siblings (§8.5.2) interesting targets in the search for life. Further encounters occur between the solar system's zodiacal cloud and other planets (Wickramasinghe et al., 2012). In star-forming groups and clusters, the chances of biological material spreading from one system to another is further enhanced (Adams & Spiegel, 2005; Belbruno et al., 2012). Suggestions that life originated 2–20 Myr after the Big Bang were made by Gibson et al. (2011a).

*Directed panspermia* contends that organisms were deliberately transmitted to Earth by intelligent beings on another planet (Crick & Orgel, 1973).

Lin & Loeb (2015) argued that the detection of 25 biologically active exoplanets could yield a  $5\sigma$  confirmation of the panspermia hypothesis.

With several habitable zone planets, TRAPPIST-1 would allow impact ejecta to be captured by its other planets on time scales of ~100 yr, with lithopanspermia some  $10^4$ – $10^5$  times faster than in the solar system (Krijt et al., 2017; Lingam & Loeb, 2017a). In general, close-proximity planet pairs in multi-habitable systems may be particularly conducive to life (Steffen & Li, 2016).

#### 11.8.4 Extraterrestrial life

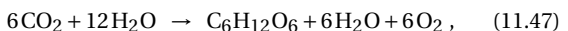
The extraterrestrial life debate has run for centuries, and many respected scientists have been proponents of life's ubiquity (box, page 639). Its existence elsewhere in the solar system is still under investigation (box, page 636), and the debate remains unresolved.

Concluding from two millennia of (sometimes wild) speculation, Crowe (1986, p552) has cautioned that one of the most pervasive fallacies has been to mistake necessary conditions for sufficient conditions: '*Until we learn the necessary and sufficient conditions for life to arise, we shall not be able to infer actual habitation of any planet from proofs of its habitability*'.

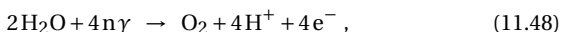
#### 11.8.5 Spectroscopic indicators

For the development of the (no longer pursued) ESA Darwin and NASA Terrestrial Planet Finder space studies (§7.7.3), an important consideration was the spectral range demanded (optical, infrared, or both), and which spectral lines might be observed with the best prospects of indicating the presence of life (e.g. Kaltenegger et al., 2010c). The arguments are founded on C-based life as presently known, and the identification of more complex chemical pathways may modify the conclusions (Saar et al., 2008; Schneider, 2008a,b; Lv et al., 2017).

**Oxygen** Owen (1980) already argued that large-scale biological activity on a telluric planet necessarily produces a large quantity of O<sub>2</sub>. Photosynthesis builds organic molecules from CO<sub>2</sub>, according to



mediated by H<sup>+</sup> ions which originate from different sources. In the case of oxygenic bacteria on Earth, H<sup>+</sup> ions are provided by the photodissociation of H<sub>2</sub>O



where  $n\gamma$  specifies the  $n$ -photon process. Terrestrial oxygenic photosynthesis uses  $n = 2$ , utilising the 'photosynthetically active radiation' of sunlight ( $\lambda = 0.4 - 0.7 \mu\text{m}$ ), and with O<sub>2</sub> produced as a by-product.

This is not the same for anoxygenic bacteria, such that O<sub>2</sub> is considered a possible, but not a necessary, by-product of life. Indeed, Earth's atmosphere was O<sub>2</sub>-free until about 2 Ga, suppressed for more than 1.5 Gyr after life originated (Kasting, 1996; Bekker et al., 2004).

Abiotic production of O<sub>2</sub> is more problematic: the main source of abiotic O<sub>2</sub> on Earth, photolysis of H<sub>2</sub>O, is only effective for ultraviolet photons, with  $\lambda < 180 \text{ nm}$  (Léger et al., 2011a). As a result, O<sub>2</sub> (and O<sub>3</sub>) absorption have been considered the most promising biosignatures of life on terrestrial exoplanets (e.g. Owen, 1980; Angel et al., 1986; Léger et al., 1993; Selsis et al., 2002; Kaltenegger et al., 2010c; Léger et al., 2011a; Harman et al., 2015; Meadows, 2017).

**The extraterrestrial worlds debate pre-1900:** The existence of other 'populated' worlds has been debated since antiquity. An extensive literature has been chronicled by Crowe (1986), on which this synopsis is based. Earlier perspectives include those of Flammarion (1880), Chamberlin (1932), McColley (1936), Engdahl & Cuffari (1974), Hoyt (1976), and Dick (1982).

The ancients of both Greece and Rome were already deeply divided. Arguing for 'plurality' was Epicurus (341–270 BCE), who developed ideas originating with Democritus and Leucippus two centuries earlier, and who wrote (op. cit., p3) '*... there are infinite worlds both like and unlike this world of ours*', adding that '*we must believe that in all worlds there are living creatures and plants and other things we see in this world*'. Opposition to the pluralist position dates at least from the time of Plato and Aristotle, Plato (428–348 BCE) asserting that (op. cit., p5) '*there is and ever will be one only-begotten and created heaven*'.

Post-Copernicus, Galileo, Descartes, Gassendi and Newton viewed such speculation as being at the limit of legitimate science (op. cit., p160). But between 1500–1750, as a consequence of astronomical, philosophical and religious developments, plurality gained the support of some of the most prominent figures of the age. '*Presented with exceptional appeal by Fontenelle, given legitimacy in scientific circles by Huygens and Newton, reconciled to religion by Bentley and Derham, ... [it was] integrated into philosophical systems by Berkeley and Leibniz, and taught in textbooks by Wolff*' (op. cit., p37). Many of the most prolific astronomers and prominent intellectuals of the 18th and 19th centuries contributed to the debate (op. cit., p547).

During the second half of the eighteenth century, plurality was embraced by many influential astronomers. Crowe (1986, p41) argues that the writings of the pioneers of sidereal astronomy (Wright, Kant, and Lambert) were permeated by pluralism, with this revolution '*intimately related to the extraterrestrial life debate*'. Thus Kant's various texts (op. cit., p55) suggest that the 'starry heavens' that so filled him with awe were '*a densely denized domain wherein millions of inhabited planets orbited suns clustered in endless hierarchies of systems*'. Similarly, the research of the period's premier astronomer, William Herschel, was deeply influenced by ideas of extraterrestrial life (op. cit., p62). His genius notwithstanding, Herschel considered that the Moon had '*the great probability, not to say absolute certainty, of being inhabited*', his lunar observations evidencing 'vegetation', 'turnpike roads', and 'circuses' (op. cit., p65). He referred to the 'inhabitants' of Mars, Saturn, and [Uranus], and of their satellites, to the fact that every star '*is probably of as much consequence to a system of planets, satellites, and comets, as our own Sun...*', while his observations of sun spots suggested that even the Sun '*... is most probably also inhabited... by beings whose organs are adapted to the peculiar circumstances of that vast globe*' (Herschel, 1795, p63). Many of his contemporaries, including Arago, Lalande, Maupertius, and Schröter, were also involved in the pluralist quest. Johann Bode advocated extraterrestrials with fervour and influence, populating essentially every celestial body – sun, star, planet, and satellite – with rational beings (op. cit., p73). Laplace's 'nebular hypothesis' explained the solar system as resulting from the rotation and contraction of a primitive solar fluid, implying that planets are an expected result of stellar evolution, and thus providing support for the pluralist contention that most stars were encircled by planets (Laplace, 1796). From the cooling times of the Earth and planets, the Comte de Buffon tabulated, in 1775, the times at which life began and would end on each (op. cit., p132).

Physicotheologians embraced extraterrestrials as evidence of God's omnipotence, while the religious saw plurality as the product of divine power and generosity. Thomas Paine's *Age of Reason* of 1793 essentially rejected Christianity because of pluralism. James Mitchell's lecture *On the Plurality of Worlds* to the London Mathematical Society in 1813 argued for life on all planets and satellites. Thomas Dick (1837) estimated the population of the solar system bodies, including the rings of Saturn (op. cit., p199). In his *Complete System of Astronomy* of 1797–1808 Samuel Vince considered that novae were '*the destruction of that system at the time appointed by the Deity for the probation of its inhabitants*'. Other eminent early 19th century astronomers were pluralists and even proponents of lunar life, with (it is believed) Gauss proposing a giant figure in Siberia to signal to the Moon or Mars, and Littrow suggesting a kerosene-lit canal in the Sahara for similar purposes (op. cit., p204).

Support for extraterrestrials received a setback with a lecture by Bessel in 1834 in which, appealing to the sharpness with which stars are occulted by the Moon, he argued that it lacks any significant atmosphere, and that it therefore has neither air nor water. Hegel raised philosophical objections to plurality, and in 1853 William Whewell published an essay claiming that many of the pluralist arguments were scientifically defective and religiously dangerous. This led to renewed debate involving, among others, physicist David Brewster, Savilian professor Baden Powell, astronomers Lord Rosse and Camille Flammarion, populariser Richard Proctor, mathematician Augustus De Morgan, and biologist Charles Darwin (op. cit., p265).

Spectroscopy, pioneered by Huggins, Ångström, the Drapers, Janssen, Lockyer, Schellen, and Secchi, led to more quantitative stellar investigations, but also provided further substance for the pluralist debate; in fact (op. cit., p360) '*to a greater extent than has been previously noted, [they] saw themselves as involved in that debate*'. In their first major spectroscopic study of nearly fifty stars, Huggins & Miller (1864) identified numerous spectral lines coinciding with the terrestrial elements, concluding that '*There is therefore a probability that these stars are... like our Sun, surrounded by planets*'. To which they added '*It is remarkable that the elements most widely diffused through the host of stars are some of those most closely connected with the constitution of the living organisms of our globe... On the whole we believe that the foregoing [observations] contribute something towards an experimental basis on which a conclusion... may rest, viz. that at least the brighter stars are, like our sun, upholding and energising centres of systems of worlds adapted to the abode of living beings*'.

Subsequent debates surrounded the varying features in the lunar crater Linné (Schmidt 1866, summarised by Moore, 1977); consequences of the lunar figure for habitability (Hansen, 1856); reports of Martian or Venusian signals, involving Nikola Tesla, Lord Kelvin, and Guglielmo Marconi; and claims of lunar vegetation by Pickering (1902). Even more recently, the Astronomer Royal Harold Spencer Jones considered it '*almost certain that there is some form of vegetation on Mars*' (Spencer Jones, 1940, p207).

A century ago saw the protracted debate (1877–1910), and substantial literature, on the question of canals on Mars. Schiaparelli, Lowell, and Flammarion were the main advocates, with Antoniadi, Campbell, and Maunder leading the anti-canal and anti-life arguments. Sixty pages in Crowe (1986) detail the controversy, its now-favoured explanation in terms of the Maunder–Cerulli theory of unconscious tendencies to see discrete details integrated into lines or circles (op. cit., p543), and more recent assessment of its context and scientific consequences (Shklovskii & Sagan, 1966; Sagan & Fox, 1975; Wells, 1979).

Owen (1980) noted the possibility, quantified by Schneider (1994b), of using the 690 nm and 760 nm bands of O<sub>2</sub> as a spectroscopic tracer of life since, being highly reactive with reducing rocks and volcanic gases, O<sub>2</sub> would disappear in a short time in the absence of a continuous production mechanism.

Plate tectonics and volcanic activity provide a sink for free O<sub>2</sub>, and are the result of internal radiogenic heating and of silicate fluidity, both of which are expected to be present whenever the mass of the planet is suffi-

cient, and when liquid H<sub>2</sub>O is present. For small enough planet masses, volcanic activity disappears some time after planet formation, as do the associated oxygen sinks.

In the near infrared, O<sub>2</sub> at 1.27 μm provides a further diagnostic (Kawahara et al., 2012; Snellen et al., 2013a). Studies continue as to whether O<sub>2</sub> is a robust biosignature (e.g. Léger et al., 2011a; Schwieterman et al., 2016), or not (e.g. Wordsworth & Pierrehumbert, 2014).

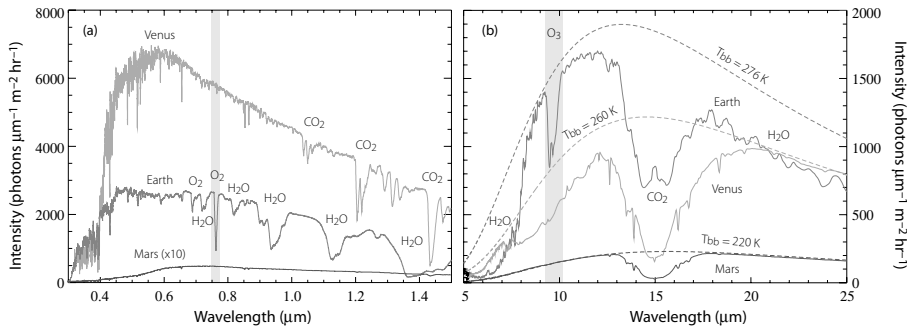


Figure 11.44: Spectra of Venus, Earth, and Mars: (a) reflection spectra (which mix solar and planetary lines) at a resolution  $\sim 100$  over the ultraviolet–visible–near infrared; (b) mid-infrared thermal emission at the same resolution, with the black-body emission of a planet of the same radius (dashed). For Venus and Mars, only CO<sub>2</sub> is observable at low-resolution. The Earth also shows the deep and sharp 9.6  $\mu\text{m}$  O<sub>3</sub> and 0.76  $\mu\text{m}$  O<sub>2</sub> bands due to life, and H<sub>2</sub>O bands. The flux corresponds to a solar system analogue at 10 pc. Spectra are model results validated by observations. Adapted from Selsis et al. (2008a, Figure 1).

**Ozone and methane** Angel et al. (1986) showed that O<sub>3</sub> is itself a tracer of O<sub>2</sub> and, with a prominent spectral signature at 9.6  $\mu\text{m}$  in the infrared where the planet/star contrast is significantly larger than in the optical, should be easier to detect. These considerations motivated the consideration of the Darwin and TPF space interferometers observing in the infrared for the study of lines such as H<sub>2</sub>O at 6–8  $\mu\text{m}$ , CH<sub>4</sub> at 7.7  $\mu\text{m}$ , O<sub>3</sub> at 9.6  $\mu\text{m}$  and CO<sub>2</sub> at 15  $\mu\text{m}$  (Woolf & Angel, 1997; Léger et al., 2015).

Higher resolution studies could reveal the presence of CH<sub>4</sub>, its presence on Earth resulting from a balance between anaerobic decomposition of organic matter and its interaction with atmospheric oxygen; its highly disequilibrium co-existence with O<sub>2</sub> could be strong evidence for life (Margulis & Lovelock, 1974; Kasting & Donahue, 1980; Léger et al., 1994a,b; Kasting, 1996; Segura et al., 2003; Selsis et al., 2008b; Court & Sephton, 2012; Guzmán-Marmolejo et al., 2013; Hedelt et al., 2013; von Paris et al., 2013b; Domagal-Goldman et al., 2014). Various caveats are reviewed by Reinhard et al. (2017).

Amongst the many observational challenges, Rein et al. (2014) argued that an abiotic planet–moon system in the habitable zone around a Sun-like star with an Earth-size planet’s atmosphere containing 20% O<sub>2</sub>, and a Titan-size moon’s atmosphere containing 50 ppm CH<sub>4</sub>, the combined reflection spectrum between 1–1.63  $\mu\text{m}$  at  $R = 100 - 2000$  would closely resemble that of a single Earth-size planet atmosphere with 15% O<sub>2</sub> and 30 ppm CH<sub>4</sub>. Multi-band near-infrared observations may permit their distinction (Li et al., 2016b).

The possibility that O<sub>3</sub> is not an unambiguous identification of Earth-like biology but rather a result of abiotic processes (Owen, 1980; Kasting, 1996; Noll et al., 1997b; Schneider, 1999; Segura et al., 2007) was examined in detail by Léger et al. (1999). They considered various production processes such as abiotic photodissociation of CO<sub>2</sub> and H<sub>2</sub>O, followed by the preferential escape of hydrogen from the atmosphere.

In addition, cometary bombardment could bring O<sub>2</sub> and O<sub>3</sub> sputtered from H<sub>2</sub>O by energetic particles (cf. the ultraviolet spectral signature of O<sub>3</sub> in the satellites of Saturn, Rhea and Dione; Noll et al. 1997b), according to temperature, greenhouse blanketing, and the presence of volcanic activity. Léger et al. (1999) concluded that a simultaneous detection of significant amounts of H<sub>2</sub>O and O<sub>3</sub> in the atmosphere of a planet in the habitable zone stands as a criterion for large-scale photosynthetic activity on the planet.

An absence of O<sub>2</sub>, on the contrary, would not necessarily imply the absence of life. However, an atmosphere rich in O<sub>2</sub> provides the largest feasible source of chemical energy, and abundant O<sub>2</sub> may be necessary for complex life anywhere, viz. for actively mobile organisms of 0.1–1 m size, and with specialised, differentiated anatomy (Catling et al., 2005). Specifically, Catling et al. (2005) argued that the partial pressure of atmospheric O<sub>2</sub> must exceed  $\sim 10^3$  Pa to allow organisms that rely on O<sub>2</sub> diffusion to evolve to a size  $\sim 1$  mm, while  $\sim 10^3 - 10^4$  Pa is required to exceed a size-threshold of 0.01 m for complex life with circulatory physiology.

**Characterising Earth-like atmospheres** Assuming adequate spectral resolution, the temperature and pressure environment of specific molecular species can be derived from the shape and width of the spectral line, notably as a result of Doppler broadening dominating at lower pressures (i.e. higher altitudes), pressure-induced Lorentz broadening dominating at higher pressures, and the temperature distribution with altitude. Distinguishing the effects of temperature structure and vertical distribution is best carried out using a species evenly mixed within the atmosphere, such as CO<sub>2</sub> on Earth, rather than more vertically inhomogeneous species such as O<sub>3</sub>, H<sub>2</sub>O, or CH<sub>4</sub> (Meadows, 2008).

Earth’s main atmospheric constituent, N<sub>2</sub>, has no strong spectral features redward of the far ultraviolet. O<sub>2</sub>

has a triplet between 0.6–0.76  $\mu\text{m}$ , and is a significant spectral feature for the Earth's atmosphere, but not for those of Venus and Mars.  $\text{CO}_2$  is a trace gas in the Earth's atmosphere, but a bulk gas on Venus and Mars, and produces strong spectral features in the mid-infrared and, for sufficient partial pressures, also in the near infrared between 1.0–1.7  $\mu\text{m}$  (Des Marais et al., 2002; Meadows, 2008; Selsis et al., 2008a; Vázquez et al., 2010). Modeled atmospheric spectra for Earth, and comparison with those of Venus and Mars, are shown in Figure 11.44.

$\text{H}_2\text{O}$  vapour absorbs strongly in the visible, near and mid-infrared, and its presence may indicate a surface ocean. Other indicators of oceans may be glints, rainbows, and polarisation (Ford et al., 2001b; Schmid et al., 2006; Stam et al., 2006; Bailey, 2007; Cowan et al., 2009; Zugger et al., 2011; Karalidi et al., 2012a).

Other spectral signatures at ultraviolet, visible, and infrared wavelengths can be used to establish molecular abundances, infer the presence of greenhouse gases, and estimate surface temperatures, and in particular to determine whether  $\text{H}_2\text{O}$  is likely to exist in liquid form, and perhaps even characterise specific surface types through spin-orbit tomography (§6.15.8), such as ocean, soil, snow, and vegetation (Schindler & Kasting, 2000; Tinetti et al., 2006a,b; Selsis et al., 2008a; Pallé et al., 2009; Fujii et al., 2010; Vidal-Madjar et al., 2010; Kawahara & Fujii, 2011; Rauer et al., 2011; Schwartz et al., 2012; Hegde & Kaltenegger, 2013; Rugheimer et al., 2013; Cataldi et al., 2017; Poch et al., 2017). Climatic effects of multi-layered clouds, as a probe of habitability, have also been modeled (Kitzmann et al., 2010, 2011a,b, 2013).

**Signatures of plant life and photosynthesis** The Earth displays specific spectral signatures due to plant life (Figure 11.45). Chlorophyll has a varying absorption with wavelength, with stronger absorption in the ultraviolet/blue and in the red as compared to  $\lambda \sim 550 \text{ nm}$ . Plants also show a sharp increase in reflectivity at  $\lambda \geq 0.7 \mu\text{m}$ , known as the *red edge*. It was observed as a distinguishing feature in the Earth's spectrum by the Galileo spacecraft during Earth fly-by (Sagan et al., 1993), and is used as the basis of vegetative remote-sensing.

The 'red edge' is considered as a possible biosignature for vegetation (Arnold et al., 2002; Seager et al., 2005b; Tinetti et al., 2006c; Arnold et al., 2009; Dougherty & Wolf, 2010; Fujii et al., 2010; Sterzik et al., 2012; Brandt & Spiegel, 2014), although only rather weak in the Earth's global spectrum (Montañés-Rodríguez et al., 2006; Hamdani et al., 2006), and not observed in Earth light reflected from the Moon (Montañés-Rodríguez et al., 2005). A comparable sharp spectral signature may be stronger on planets with different forms of plant life, or may appear at different wavelengths for planets around stars of different spectral type (Franck et al., 2001; Wolstencroft & Raven, 2002; Raven & Cockell, 2006; Tinetti et al., 2006b; Kiang et al., 2007a,b).

**Earthshine:** Sunlight scattered by Earth illuminates the side of the Moon facing away from the Sun. This *Earthshine* represents Earth's total spatially-unresolved brightness, analogous to that of an exoplanet. Measurements can be used to identify disk-averaged spectral features, including metal lines, vegetation, and other biomarkers (Goode et al., 2001; Arnold et al., 2002; Woolf et al., 2002; Seager, 2003; Hamdani et al., 2006; Turnbull et al., 2006; Montañés-Rodríguez et al., 2006, 2007; Arnold, 2008; Langford et al., 2009; González-Merino et al., 2013; Pallé et al., 2016b).

Other properties may be determinable from intra-day photometric variability (Ford et al., 2001b; Seager, 2003; Pallé et al., 2008a), and from spectropolarimetry (Sterzik et al., 2012; Miles-Páez et al., 2014).

Earthshine is dominated by a relatively small region of the hemisphere visible from the Moon due to the viewing angle (Des Marais et al., 2002; Seager et al., 2005b; Pallé et al., 2008a). Fresnel (specular) reflection dominates in oceanic regions, which otherwise have a low albedo (Sagan et al., 1993). Rotation of land (which scatters diffusively) onto the location of this bright spot interrupts the specular reflection, which leads to a predictable decrease in Earthshine flux (Ford et al., 2001b; Tinetti et al., 2006b; Williams & Gaidos, 2008). Clouds, covering some 60% of Earth's surface, increase its albedo and dominate the scattered light, although they are generally tied to surface features, dissipate on time scale of days, and therefore do not vary greatly during typical observations (Pallé et al., 2008a).

Small temporal variations in  $\text{CO}_2$  and  $\text{CH}_4$  also arise on Earth as a result of seasonal changes in patterns of photosynthesis (Tucker et al., 1986).

**Earth's spectrum over geological history** The Earth's atmosphere has evolved significantly over geological time (§12.3.8). To model the observable spectra of an Earth-like planet throughout its history, and to guide interpretation of an observed Earth-like planet by an instrument such as Darwin or TPF, Kaltenegger et al. (2007) characterised the atmosphere at six epochs extending from 3.9 Gyr ago to the present day.

Based on reflectance spectra of specific compositional features such as snow, sand, sea and vegetation (Figure 11.46a), they constructed visible and near-infrared spectra based on estimated surface abundances of  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{O}_2$ ,  $\text{O}_3$ , and  $\text{N}_2\text{O}$ . Example results, for an Earth-like planet in the absence of clouds, are shown in Figure 11.46b. Other related studies have been made (e.g. Grenfell et al., 2011; Hasenkopf et al., 2011; Sanromá et al., 2013, 2014).

Arney et al. (2017) considered detectability of the absorption features of organic hazes, of the form suggested by geochemical evidence for an early (Archean, 3.8–2.5 Ga) Earth (e.g. Pavlov et al., 2001b; Hicks et al., 2016). Evidence for past existence of this haze centres around correlations between sulphur and organic carbon isotopes which imply that the surface ultraviolet flux was attenuated while the atmospheric redox state remained reducing.

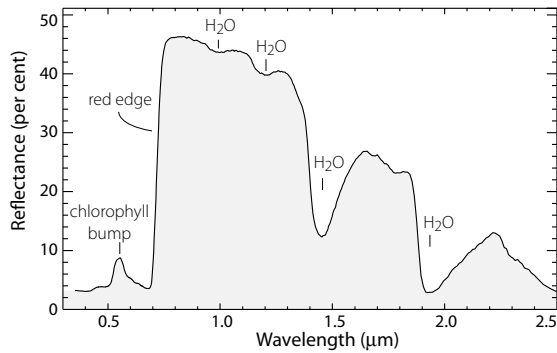


Figure 11.45: Reflection spectrum of a deciduous leaf. The bump near 550 nm is due to chlorophyll absorption (at 450 nm and 680 nm), which gives plants their green colour. The sharp rise between 700–800 nm, the red edge, is due to the contrast between the strong absorption of chlorophyll and the otherwise reflective leaf. Adapted from Seager et al. (2005b, Figure 1).

**Searches for water** Even for a planet within the habitable zone where liquid water is possible, the presence of H<sub>2</sub>O is ambiguous based on mass and radius alone. Direct spectroscopic detection in exoplanet atmospheres has been obtained for about a dozen objects, mainly hot Jupiters (§11.6.2). The first detections were for HD 189733, from Spitzer (Tinetti et al., 2007b), and subsequently from HST–NICMOS (Swain et al., 2008b). For the hot Saturn WASP–39 b, near-infrared HST–WFC3 transmission spectra shows three H<sub>2</sub>O-absorption features (0.95, 1.2, and 1.4 μm), and a well-constrained  $T_{\text{eq}} = 1030_{-20}^{+30}$  K (Wakeford et al., 2018).

Extending the technique to smaller and cooler planets has been a challenge. For several planets (e.g. Knutson et al., 2014b; Kreidberg et al., 2014b) the transmission spectrum is dominated by other clouds, basically hiding the H<sub>2</sub>O-absorption signature. Ground-based high-dispersion spectroscopy of hot Jupiters has also resulted in several water detections, starting with near-infrared (3–3.5 μm) detection in the day-side thermal spectrum of HD 189733 using VLT–CRIRES (Birkby et al., 2013), and in  $\tau$  Boo using Keck–NIRSPEC (Lockwood et al., 2014). High-contrast imaging has also revealed water absorption in young massive gas giants at large orbital distances. Orbiting the young A-giant HR 8799, both planets b and c exhibit a clear water absorption signature, together with CO and CH<sub>4</sub>, and CO respectively (Barman et al., 2015; Konopacky et al., 2013). The detection of water in the atmosphere of terrestrial planets is challenging and awaits future instrumentation such as JWST and the next generation of ELTs.

A review of the recent progress in observations of water-rich exoplanets, the detection of water in the atmosphere of gas giants and less-massive targets, and the modelling of the interior and evolution of water layers in exoplanets, is given by Noack et al. (2017b).

**Water masers:** Cosmic thermal H<sub>2</sub>O emission is not easily detected with ground-based telescopes because of the large quantity in Earth’s lower atmosphere. However, non-thermal emission in the form of maser lines is a widespread phenomenon. Transitions originate between specific rotational levels, and the required pumped population inversion, large column density, and suitable velocity coherence, can occur naturally under certain conditions. Maser lines, at various frequencies, have been detected in (extra-)galactic interstellar clouds, in late M dwarfs, and in the Saturn system (Cheung et al., 1969; Mumma, 1993), and during the impact of comet Shoemaker–Levy 9 with Jupiter in 1994 (Cosmovici et al., 1996). H<sub>2</sub>O-masers have been suggested as a diagnostic in exoplanet systems where cometary bombardment is ongoing and, albeit time variable due to rotation, in upper layers of planet atmospheres more generally (Cosmovici et al., 2000).

An unsuccessful search for H<sub>2</sub>O masers towards 18 exoplanets using the Australia Telescope Compact Array, and the 22.235 GHz line (1.35 cm; levels 6<sub>16</sub> – 5<sub>23</sub>), was reported by Minier & Lineweaver (2006). Cosmovici & Pogrebenko (2018) used the 32-m Medicina and Noto radio telescopes (ITA) between 1999–2012 to observe 17 targets. They reported H<sub>2</sub>O-maser emission in  $\epsilon$  Eri, GJ 581, and Lalande 21185. They concluded that emission from the young star  $\epsilon$  Eri is associated with cometary impacts (cf. Greaves et al., 1998). For the older systems, emission was attributed to H<sub>2</sub>O-rich planet atmospheres, with maser pumping of the levels provided by photo-deposition.

At early evolutionary phases, near-infrared interferometry first spatially and spectrally resolved H<sub>2</sub>O interior to 1 au in the young star MWC 480 (Eisner, 2007), attributed to sublimation of migrating icy bodies.

**Other spectroscopic biosignatures** Other potential biosignatures, especially if seen with O<sub>2</sub>, could include the products of biomass burning, such as CH<sub>3</sub>Cl and N<sub>2</sub>O, which may be more prominent for planets around M dwarfs (Segura et al., 2005; Grenfell et al., 2007b).

Other studies have noted the possible relevance of biogenic sulphur gases as biosignatures in anoxic planets (Domagal-Goldman et al., 2011), and of NH<sub>3</sub> in the context of biomass models (Seager et al., 2013a).

To maximise prospects of recognising biosignature gases, Seager et al. (2016) have suggested that all stable and potentially volatile molecules should initially be considered as viable biosignature gases, and have systematically constructed lists of volatile molecules in different categories. Their exhaustive list for up to six non-H atoms totals ~14 000 molecules, of which 2500 are CNOPSH compounds.

Meanwhile, photochemically produced CO can be readily detected at 1.58, 2.34, and 4.67 μm, and may be considered an *anti-biosignature* (Wang et al., 2016d).

**Photometric biosignatures** Krissansen-Totton et al. (2016) investigated identification of Earth-like planets using broad-band ultraviolet to near-infrared photometry. They found that subtle features in Earth’s reflectance

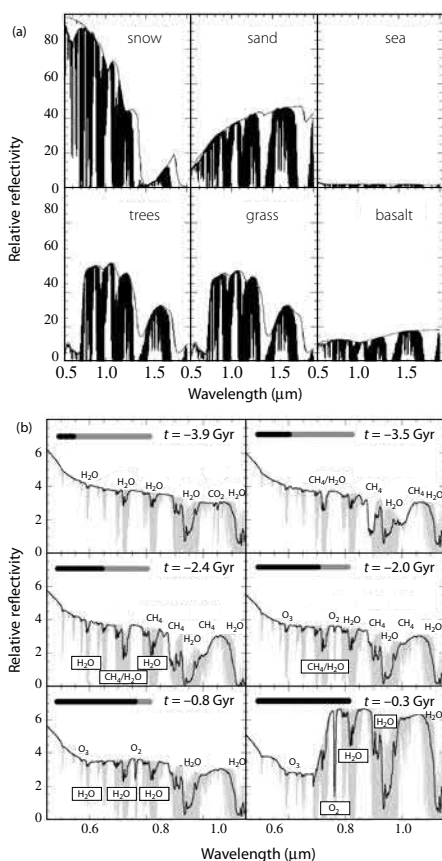


Figure 11.46: Spectra of an Earth-like planet over geological time, in the absence of clouds: (a) the contribution to a present-day atmosphere of distinct surface features; (b) visible/near-infrared spectra of an Earth-like planet at six geological epochs. The spectral lines (grey) change significantly as the planet evolves from  $\text{CO}_2$ -rich ( $-3.9$  Gyr), through  $\text{CO}_2/\text{CH}_4$ -rich ( $-2.4$  Gyr), to a present-day atmosphere (lower right). Solid curves show a spectral resolution of 70, comparable to the earlier TPF-C mission concept. From Kaltenegger et al. (2007, Figures 1 and 9), by permission of IOP Publishing/AAS.

spectrum appear to be unique, in particular its  $\sim$ -shape arising from a combination of an  $\text{O}_2$ -rich oxidising atmosphere allowing prominent Rayleigh scattering, with  $\text{O}_3$  absorption. They also found that an Archean Earth is more difficult to identify than a modern Earth twin.

**Wavelength coverage and spectral resolution** In their summary assessment of the wavelength coverage and spectral resolution for a desirable space mission, Encrenaz et al. (2015) conclude as follows:

(1) coverage from the visible to beyond  $10 \mu\text{m}$  is required to capture the variety of planets at different temperatures, detect the various chemical components in exoplanet atmospheres, provide redundancy and improved detection reliability with the detection of a molecule in multiple spectral bands, and enable an optimal retrieval of the chemical abundances and thermal profile;

(2) coverage from  $0.55\text{--}11 \mu\text{m}$  will guarantee that the key species ( $\text{H}_2\text{O}$ ,  $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{NH}_3$ ) and other important species (including Na, K, VO, TiO, TiH, CrH,  $\text{H}_2\text{S}$ ,  $\text{SO}_2$ , SiO,  $\text{H}^{3+}$ ,  $\text{C}_2\text{H}_2$ ,  $\text{C}_2\text{H}_4$ ,  $\text{C}_2\text{H}_6$ ,  $\text{PH}_3$ , HCN) can be detected in all planet types, with the exception of  $\text{CO}_2$  and  $\text{C}_2\text{H}_6$  in temperate atmospheres. The limit at  $0.55 \mu\text{m}$  is constrained by Na absorption at  $0.59 \mu\text{m}$ . The boundary at  $11 \mu\text{m}$  is constrained by  $\text{NH}_3$  absorption at  $10.5 \mu\text{m}$ .

(3) the range  $0.55\text{--}11 \mu\text{m}$  should ensure retrieval of most molecular abundances and thermal profiles, especially for gaseous planets, with an increasing difficulty in retrieval for colder atmospheres;

(4) extension to  $16 \mu\text{m}$  would favour the study of colder exoplanets, and guarantee that  $\text{CO}_2$  and  $\text{C}_2\text{H}_6$  can be detected in them. It would also offer the possibility of detecting additional absorption features from HCN,  $\text{C}_2\text{H}_2$ ,  $\text{CO}_2$  and  $\text{C}_2\text{H}_6$  for all other planets, and improve the thermal profile retrieval;

(5) extension down to  $0.4 \mu\text{m}$  would improve the detection of Rayleigh scattering/cloud contribution and stellar characterisation;

(6) a resolving power  $R = 300$  for  $\lambda < 5 \mu\text{m}$  should permit the detection of most molecules/atoms at any temperature. At  $\lambda > 5 \mu\text{m}$ ,  $R = 30$  is sufficient to detect key molecules at higher temperatures, due to line broadening. For temperate planets,  $R = 30$  at longer wavelengths is also optimal, given the limited photon numbers.

### 11.8.6 Search for intelligent life

The search for extra-terrestrial intelligence (SETI) is motivated by the belief that intelligent life is likely to emerge under conditions similar to those on Earth (e.g. Cocconi & Morrison, 1959; Drake, 1961; von Hoerner, 1961, 1973; Townes, 1997; Leigh & Horowitz, 1997; Bhathal, 2000; Tarter, 2001a; Drake, 2008; Ćirković, 2013; Cabrol, 2016).

Loosely connected but not implicit in such searches are various unproven and somewhat inconsistent postulates, amongst them the ‘anthropic principle’ (§11.7.3, which suggests that no assertion can be made about the probability of intelligent life based on a sample set of one); the ‘mediocrity principle’ (which, given the existence of life on Earth, asserts that life typically exists on Earth-like planets throughout the Universe); and the ‘fine-tuning hypothesis’ (which asserts that the natural conditions for intelligent life are implausibly rare).

Attempts to quantify the probability that intelligent life exists elsewhere in the Galaxy include consideration of the Drake equation (box, page 644), and consideration of the *Fermi paradox* (§11.8.7), viz. ‘If other advanced civilisations exist, where are they?’. Resolution of these questions may still lie far in the future.

Amongst coordinated efforts, the privately funded SETI Institute (Mountain View, California), founded in 1984, now employs 130 scientists, educators, and support staff. Activities are conducted by the Carl Sagan

Center for the Study of Life in the Universe, the Center for Education, and the Center for Public Outreach.

SETI is generally not (yet) perceived as an activity which merits public funding, and is (with some exceptions) an aside to mainstream research. Broader support has even waned since the conference on Communicating with Extraterrestrial Intelligence in 1973 (Sagan, 1973a) for which the introduction states: *'This is the proceedings of a remarkable conference on a subject which, only a few years ago, would have been considered an unthinkable topic for serious scientific discussion'*. Participants then included Nobel laureates Francis Crick, Vitaly Ginzburg, and (US government advisor) Charles Townes, and other notable academicians including Victor Ambartsumian, Freeman Dyson, Thomas Gold, Martin Harwit, Philip Morrison, and Carl Sagan.

Searches for (intentional or accidental) signals from extraterrestrial intelligence rest on insights as to what type of signal to search for, where to look and, for some search strategies, when to look (e.g. Tarter, 2001a,b; Shostak, 2011a,b; Fridman, 2011).

**Radio/microwave searches** NASA's High Resolution Microwave Survey was an early search for continuous and pulsed radio signals generated by extrasolar technological civilisations. It consisted of an all-sky survey between 1–10 GHz, as well as a targeted search of 1000 nearby stars at higher spectral resolution and sensitivity in the 1–3 GHz range. When Congress terminated the survey in 1993, the SETI Institute raised private funds to continue the search for nearby Sun-like stars as Project Phoenix (Morison, 2006). It used the Parkes 64-m telescope to observe 200 stars, the Green Bank 140-foot telescope between 1996–1998, and the Arecibo 300-m radio telescope. In total, Project Phoenix surveyed 800 stars within 65 pc, between 1.0–3.0 GHz at 1 Hz resolution. No signals were reported (Backus, 2002).

Early radio searches were also carried out at Nancy (Biraud, 1983; Heidmann, 1989; Gulkis et al., 1990).

A joint effort by the SETI Institute and the University of California, Berkeley, the Allen Telescope Array (ATA) began construction of a dedicated facility at Hat Creek (Tarter, 2006). The array was to consist of  $350 \times 6.1$ -m dishes, a bandwidth of 0.5–11 GHz, and some 10 000 target stars per year. Reaching 42 operational antennas in 2007, UC Berkeley exited the project in April 2012. As of 2016, the SETI Institute performs SETI observations for 12 hr per day (Harp et al., 2016b,a).

As of 2010, UC Berkeley was involved in 7 SETI programmes at radio, visible, and infrared wavelengths including, in the radio, the Fly's Eye experiment at ATA, and Astropulse at Arecibo (Siemion et al., 2010). Continuing SETI surveys at Arecibo, building on the earlier Serendip surveys (e.g. Werthimer et al., 2000), include the commensal ('piggy-back') SETIBURST backend equipped with the SETI spectrometer SERENDIP VI

**The Drake equation:** The 'Drake equation' was formulated by Frank Drake as a framework for evaluating the probability of the existence of alien life. In its original form (Sagan, 1973a, pp5–6; see also Bracewell 1976) the number of technical civilisations in the Galaxy at the present time, at or beyond our level of technology, is expressed as

$$N = R_{\text{SF}} f_{\text{p}} n_{\text{e}} f_{\text{l}} F_{\text{i}} F_{\text{c}} L. \quad (11.49)$$

$R_{\text{SF}}$  is the star formation rate (stars per year) averaged over the Galaxy lifetime [astrophysics];  $f_{\text{p}}$  = fraction of stars with planetary systems [astrophysics];  $n_{\text{e}}$  = mean number of planets in such systems suitable for life [astronomy/biology];  $f_{\text{l}}$  = fraction of such planets on which life originates [organic/biochemistry];  $F_{\text{i}}$  = fraction of such planets on which intelligence in some form arises [evolutionary biology/neurophysiology];  $F_{\text{c}}$  = fraction of such planets developing a communicative phase [anthropology];  $L$  = mean lifetime of such technical civilisations [sociology/psychology/politics]. Confidence in the estimated probabilities degrades strongly for successive terms.

The equation has been used by optimists and pessimists with widely different results, ranging from estimates of  $N \sim 10^6$  by Sagan (1966), to  $N \ll 1$  by Barrow & Tipler (1986). The values summarising the 1961 meeting at which the Drake equation was conceived are:  $R_{\text{SF}} = 10 \text{ yr}^{-1}$ ,  $f_{\text{p}} = 0.5$ ,  $n_{\text{e}} = 2$ ,  $f_{\text{l}} = 1$ ,  $F_{\text{i}} = 0.01$ ,  $F_{\text{c}} = 0.01$ , and  $L = 10000 \text{ yr}$ , yielding  $N = 10$  such civilisations in the Galaxy.

In the subsequent 50 years, the panorama has not changed fundamentally, although individual terms can be considered in much greater depth (Vakoch & Dowd, 2015). Today,  $R_{\text{SF}}$  and  $f_{\text{p}}$  are based on direct observation and remain reasonable estimates. A smaller value of  $n_{\text{e}} \sim 0.1$  appears to be more realistic. The speed with which life arose on Earth, whether by abiogenesis or by panspermia, is often taken to imply that life took hold as soon as conditions were suitable ( $f_{\text{l}} \sim 1$ ). The remaining terms are little more than guesses, based on little or no information, with  $L$  being particularly speculative. Values of  $N < 1$  still appear plausible, implying that there is 'nobody else out there'.

There is a substantial literature on the overall approach, and on the estimability and pitfalls of the various terms, including its temporal dependency (e.g. Chyba, 1997; Ćirković, 2004b; Glade et al., 2012; Rossmo, 2017; Simpson, 2017b). Amongst these, postulating that the statistics of planet habitability is based on a set of 10 astrophysical requirements (Dole, 1964), Maccone (2011c) derived a number of habitable planets in the Galaxy as  $100 \pm 200$  million, with an average separation between habitable pairs of  $40 \pm 20 \text{ pc}$ . The contribution of Kepler has also been discussed (e.g. Wandel, 2015; Ramirez et al., 2018).

(Chennamangalam et al., 2017, and references).

Fast radio transients (or fast radio bursts, FRBs), as possible SETI candidates, are also being searched through targeted observations of planet candidates in the Kepler field using the Green Bank Telescope (Siemion et al., 2013), as well as through the SETIBURST-ALFABURST survey at Arecibo. The latter uses commensal data recorded with the Arecibo ALFA receiver, searching for brief wide-band pulses in a 2.5 MHz band centred at 1420 MHz (Gautam et al., 2014).



The upgraded VLA is now also being used for SETI. Arguing that observing nearby galaxies would facilitate the search for artificial radio signals by sampling several billion stars simultaneously, Gray & Mooley (2017) report non-results for a 21-cm survey of M31 and M33 between 2014 December and 2015 January.

The 2-planet system GJ 581 was the target of the first VLBI SETI search, with limits of  $7 \text{ MWhz}^{-1}$  on the power of any isotropic emitter (Rampadarath et al., 2012).

The ‘Breakthrough Listen’ initiative is using the Green Bank and Parkes telescopes at various radio frequencies to search for SETI-type transmissions.<sup>5</sup> The objective is to use improved digital electronics and multi-beam receivers giving high sensitivity to a variety of signal types, including narrow-band sources in the Galactic plane, and spatially extended nearby galaxies, such as M31 and the LMC/SMC. Acquiring data since January 2016, results from the first year are described by Isaacson et al. (2017). Enriquez et al. (2017) give (null) results from 692 nearby stars observed with Green Bank at 1.1–1.9 GHz, concluding that none are continuously transmitting with an EIRP of  $10^{13} \text{ W}$ , suggesting that fewer than 0.1% of stellar systems within 50 pc operate with such systems.

Detection prospects using the Murchison Widefield Array (MWA) are described by Tingay et al. (2016). Considerations for the Square Kilometer Array (SKA) assess detection prospects to  $\sim 100 \text{ pc}$  (Tarter 2004, their Table 1; Forgan & Nichol 2011; Siemion et al. 2015).

**False alarms** The SETI episode in the 1967 discovery of pulsars is recounted by Penny (2013). The Cambridge radio astronomy group became the first to confront the ‘contact’ problem which the SETI community faces its ‘detection and reply protocols’. Meanwhile, most of the ‘interesting’ signals so far detected have been transient and non-repeatable, perhaps the first points in a growing database of signals used to construct a probabilistic argument for the existence of signals (Hair, 2013).

In the direction of known exoplanets, a radio burst towards HD 164595 by RATAN-600 (Zelenchukskaya, Russia) on 2015 May 15 was noted as a candidate signal. Other various related claims have been made, but without assessable details are not described further.

**Motivation for optical searches** The search for *optical signals* was considered already by Schwartz & Townes

<sup>5</sup> Breakthrough Initiatives is a programme to search for extraterrestrial intelligence, founded by Yuri Milner in 2015. It comprises ‘Breakthrough Listen’, to search a million stars for artificial radio or laser signals; ‘Breakthrough Message’, to create a message ‘representative of humanity and planet Earth’; ‘Breakthrough Starshot’, to send probes to the nearest star at 0.2c; and ‘Breakthrough Watch’, to identify and characterise Earth-like planets around  $\alpha \text{ Cen}$  and other stars within 20 light years.

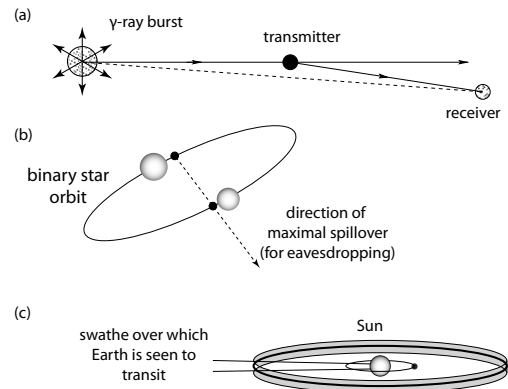


Figure 11.47: Examples of optimised SETI search strategies. In (a), a  $\gamma$ -ray burst is used as timing and positional marker: a civilisation advertising its existence sends a ‘downstream’ signal (i.e.,  $\sim 180^\circ$  away from the burst) immediately on receiving the burst signal; the receiving civilisation searches close to the burst direction, and can estimate the precise time delay of any anticipated signal from the upstream astrometry. In (b), a search focuses on detecting spillover radiation from ‘stepping-stone’ civilisations communicating between binary star hosts. In (c), civilisations within Earth’s ‘transit zone’ would know of its habitability from their own transit studies.

(1961). The principle generally adopted since is based on intercepting targeted interstellar laser communications. Current searches aim to detect a brief (few ns), intense light pulse with fast photon detectors. Its feasibility is founded on current lasers which allow for directional pulses that outshine the broad-band visible light of the Sun by at least  $10^4$  (Kingsley, 2001; Shuch, 2001; Wright et al., 2001; Mankevich & Orlov, 2016).

Recent progress in laser technology has generated laser pulses of  $\sim 1 \text{ TW}$  over many picoseconds (LLNL; Moses et al., 2013a). Such pulses, beamed by 8–10 m reflectors, create a photon flux that exceeds that of the host star, which can be distinguished from background signals, and which could be detected across the Galaxy.

Research in optical communication has also demonstrated advantages in using radiation with high values of photon orbital angular momentum (box, page 336). Endowing a single photon with orbital angular momentum  $N\hbar$  allows it to carry  $\log_2 N$  bits of information, in place of the single bit allowed by photon *spin* (Vaziri et al., 2002). Another advantage for SETI would be the absence of naturally occurring photons with high orbital angular momentum, such that artificially generated photons would be more readily identified (Harwit, 2003).

**Optical pulsed searches** Various search programmes have been undertaken. A group at UC Berkeley has been searching at optical wavelength since 1997. More recently, they have searched for narrow-band coherent signals in the spectra taken as part of their planet search programmes at Lick, Keck, and the AAT (Werthimer

et al., 2001; Korpela et al., 2011; Tellis & Marcy, 2015).

An optical search has been underway at Harvard since 1998 (Horowitz et al., 2001), for a time in synchronised mode with Princeton. A search for repetitive n-pulsed signals from a list of 13 000 Sun-like stars has been operational since 2006 (Howard et al., 2004, 2007).

Optical SETI observations started at Lick in 2000 (Wright et al., 2004b). A search of 4605 Hipparcos stars within  $\sim 60$  pc was reported by Stone et al. (2005). Lick's Automated Planet Finder is also being used to search for optical transmissions as part of 'Breakthrough Listen' (Isaacson et al., 2017; Tellis & Marcy, 2017).

A two-telescope dual-channel system has been used for a similar programme at the University of Western Sydney (Bhathal, 2001), while single-photon techniques for the detection of periodic extraterrestrial laser pulses have also been initiated in Vienna (Leeb et al., 2013).

Two searches for optical flashes have targeted KIC-8462852 (Boyajian's star;  $\$6.14.22$ ): at Boquete, Panama (Schuetz et al., 2016), and from 9 hr of serendipitous searches in 2009–15 with the VERITAS gamma-ray observatory (Abeysekara et al., 2016).

**Infrared pulsed searches** A similar approach is being developed in the near infrared, 950–1650 nm, in part to exploit the lower extinction at low Galactic latitudes. NIROSETI uses avalanche photodiodes (APDs) with low noise and  $>1$  GHz bandwidth (Maire et al., 2014b; Wright et al., 2014c).

**Optical spectral searches** Searches for non-natural signals in existing astronomical spectra have also been considered. These include searches for anomalous spectral lines from radioactive fissile waste, such as technetium (Whitmire & Wright, 1980; Paprotny, 1977). Reines & Marcy (2002) used Keck–HIRES to search 577 nearby stars for lines too narrow to be natural, and thus attributable to laser emission. Tellis & Marcy (2017) extended the search to 5600 stars covering 364–789 nm.

Assuming communicating civilisations employing a 10-m class telescope, their limits on directed laser power range from 3 kW to 13 MW. For the sample containing roughly 2000 luke-warm, Earth-size planets, they rule out models of the Milky Way in which over 0.1% of warm, Earth-size planets harbour technological civilisations that, intentionally or not, are beaming optical lasers towards Earth (detection limits for pulsed emissions are described in their Section 6). A related sample of 1709 stars is being observed between 2016–18 with the 2.4-m APF telescope as part of the 'Breakthrough Listen' initiative (Isaacson et al., 2017; Tellis & Marcy, 2017). Lin et al. (2014) assessed the spectral signatures of anthropogenic-type atmospheric pollution, and JWST's ability to detect CFCs such as CF<sub>4</sub> and CCl<sub>3</sub>F.

**Fourier content** Time variations of the intensity of a pulsating source with periods  $10^{-10} - 10^{-15}$  s would modulate its spectrum with periodicity detectable in (the Fourier transform of) standard astronomical spectra (Chin et al., 1992; Borra, 2010, 2012b).

Fourier analysis of 2.5 million SDSS spectra revealed signals, of identical period, in 234 F2–K1 stars, replicating the signatures of closely-separated pulses with  $\Delta t \sim 1.6 \times 10^{-12}$  s (Borra & Trotter, 2016). They hypothesised a SETI origin and speculated, along the lines of a common protocol, as to why all 234 transmitters would broadcast with the same pulse-time

separation. Tamburini & Licata (2017) conjectured instead that this could be the first indirect evidence of axion-like ultralight Dark Matter field effects in main sequence stars.

**Gamma-ray searches** The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) has been used, as a  $\gamma$ -ray detector (Holder, 2005), to search for ns laser pulses from 187 nearby potential habitable systems (Hanna et al., 2009).

**High-frequency gravitational waves** In a wider review of associated detector developments, Baker (2017) argues that advanced civilisations might use (non-attenuating) high-frequency gravitational waves ( $>100$  kHz) for interstellar and other communications.

**Alien engineering** Other optical searches have targeted anomalous features in Kepler photometry that could point to the alteration of an alien environment such as a *Dyson sphere* (Wright et al., 2014b,a; Ćirković, 2015; Griffith et al., 2015; Wright et al., 2016b).

Guillochon & Loeb (2015) assessed detectability as light leakage from 'light sails' in multi-transiting systems. Gaidos (2017b) considered prospects for the in-transit detection of reflectors or scatterers near the inner Lagrange point positioned as a geoengineering solution to anthropogenic climate change. Lingam & Loeb (2017b) considered the detection of large-scale photovoltaic arrays, positioned to harness energy, from their distinctive spectral features.

Lacki (2016) argued that the energy spectrum of the Planck Compact Sources excludes Kardashev Type III societies, viz. those with Galactic-scale engineering, for 3 million galaxies containing  $\sim 300 \times 10^{15}$  terrestrial planets. Other limits are set by Zackrisson et al. (2015).

**Other concepts** Exploiting amplification inherent in solar gravitational lensing (§5.7), a spacecraft anywhere along the Sun's focal line could observe and communicate over interstellar distances, using equipment comparable with that now used over interplanetary distances (Eshleman, 1979; Drake, 1988; Cohen, 1988). Use of a 70-m telescope, Colossus, has also been proposed (Berdyugina et al., 2014; Kuhn et al., 2014; Moretto et al., 2014; Kuhn & Berdyugina, 2015).

**Search strategies** Specific SETI search strategies attempt to address the problem of how and where to look.

**Catalogue of Nearby Habitable Systems** For its targeted search programmes, the SETI Institute's Catalogue of Nearby Habitable Systems (Turnbull & Tarter, 2003a,b) was created for Project Phoenix from the Hipparcos Catalogue. Distances (for signal propagation), variability (for climate stability), multiplicity (for orbital stability), kinematics (as a metallicity indicator), and spectral classification, were complemented by X-ray luminosity, Ca II H and K activity, rotation, spectral types, kinematics, metallicity, and Strömberg photometry.

Studies of evolutionary tracks, orbital stability, and habitable zones, yielded 17 129 habitable (star) candidates in the Sun's vicinity, of which 75% lie within 140 pc, and some 2200 are known or suspected to be in binary or triple systems.

**Other search strategies** Other insights can be used to suggest search strategies which might offer improved detection prospects. The following provides a flavour.

When transmitting a signal over large distances, it is more efficient to send a brief beamed signal than a continuous omnidirectional transmission, but this requires that the receiver knows where, and when, to look. Corbet (1999) argued that

**The Fermi (or Fermi–Hart) paradox:** *‘Where is everybody?’* is the question famously posed by Enrico Fermi in 1950 (as cited by Sagan 1963, p495; see also Jones 1985). Alternatively formulated as *‘If alien civilisations existed, they would be here’*, or as the ‘Great Silence’ problem, it is a deceptively simple question that presents a challenge for theories assuming a naturalistic origin of life and intelligence. Further developed by Hart (1975), Viewing (1975), Tipler (1980, 1981) and Bracewell (1981), it has since been debated in an extensive and often speculative literature (see reviews by Brin, 1983; Webb, 2002; Ćirković, 2009; Davies, 2010; Webb, 2011). Ćirković (2009) considers it *‘the last challenge for Copernicanism’*, and as *‘... arguably the biggest challenge for any practical SETI activity, as well as the least understood of the ‘grand questions’ posed in the history of science’*.

Existence probabilities for other civilisations are largely founded on arguments of scale, which run broadly, and in order of increasing uncertainty (Tipler, 1980, 1981): (i) that the Sun is relatively young, and there are billions of stars in the Galaxy that are significantly older; (ii) some are likely to have Earth-like planets which, if Earth is typical, may develop intelligent life; (iii) some of these are likely to develop interstellar travel; (iv) under plausible assumptions, including a civilisation’s average lifetime, they are likely to have explored or colonised the Galaxy on time scales of 1 – 100 Myr.

The paradox then arises as the apparent contradiction between probability estimates of the existence of such civilisations, and the absence of evidence either for visits (e.g. of alien space probes) or for intelligent life elsewhere in the Galaxy. The latter includes (absence of) SETI-type signals (Tarter, 2001a), evidence of ‘astroengineering’ projects such as Dyson spheres (Dyson, 1960; Sagan & Walker, 1966; Slysh, 1985; Timofeev et al., 2000; Jugaku & Nishimura, 2004), short-lived isotopic stellar spectral lines (Valdes & Freitas, 1986), artificial satellite transits (Arnold, 2005a), and others (Freitas, 1980, 1985; Harris, 1986). Viewed by Almar (1992) as analogous to Olbers’ paradox in classical cosmology, intentional or unintentional manifestations of advanced civilisations should be widely manifest; that this is not so appears to point to some flaw either in assumptions or reasoning.

One resolution of this paradox is that alien civilisations simply do not exist. In this scenario, Earth is unique (within the Galaxy, if not the Universe) in harbouring intelligence. This may be because, even though life appeared early in Earth’s geological history (e.g. Mojzsis et al., 1996), it may nonetheless be highly improbable (quantified in Bayesian terms by Spiegel & Turner, 2012). Although even early laboratory experiments suggested that simple molecules in Earth’s primeval atmosphere could form sugars, amino acids, and other life-related organic substances if supplied with free energy (Fox & Dose, 1972), and while a large and growing number of organic molecules of moderate complexity are now known to be widespread in both circumstellar and interstellar media (e.g. Herbst & van Dishoeck, 2009), proceeding from amino acids to proteins, or from nucleotides to nucleic acids, may be combinatorially implausible, requiring that the substantial ‘information gap’ is bridged by some (unknown) proto-Darwinian evolution (Argyle, 1977).

Even if simple life forms develop, it may still be that the number of evolutionary pathways leading from unicellular organisms to intelligent life is minute compared with the total number of possible pathways (Tipler, 1980). Or, as in the ‘rare-Earth’ class of hypotheses expounded by Ward & Brownlee (2000), while simple life forms might be ubiquitous (as evidenced by the extremophiles), complex biospheres like the Earth’s may be very rare due to the exceptional combination of many distinct requirements (involving, amongst others, the habitable zone, the presence of the Moon and Jupiter, the importance of rare elements, and of rare Cambrian-explosion type analogues).

Contrasting with the uniqueness view, and underlining the fact that absence of evidence is not evidence of absence, many other explanations for the non-existence of ‘visits’ have been put forward. They can be grouped as (cf. Hart, 1975; Ćirković, 2009): (i) physical: some fundamental difficulty (physical, astronomical, biological, or engineering) makes space travel impossible (arguments against this were given by Tipler, 1980, 1981); (ii) sociological: extraterrestrials have not visited Earth, either by choice (for reasons varying from political to lack-of-interest, e.g. Lampton 2013), because of more complex population dynamics resulting in a Galaxy which is, or seems to be, empty (Turner, 1985; Ostriker & Turner, 1986; Haqq-Misra & Baum, 2009; Starling & Forgan, 2014), or due to the limited longevity of technological civilisations, itself due either to consistent self-destruction (e.g. social collapse or nuclear annihilation), or to cosmic extinctions which consistently reset the astrobiological clocks, such as  $\gamma$ -ray bursts (Annis, 1999; Vukotić & Ćirković, 2007; Galante & Horvath, 2007), cometary or asteroid impacts (Horner & Jones, 2012b), or supervolcanic eruptions (Rampino, 2002); (iii) temporal: advanced civilisations have arisen only recently, with insufficient time to reach us; (iv) visits have occurred, including the ‘directed panspermia’ of Crick & Orgel (1973), but are not presently observed (assuming the broadly-held astronomical position that claimed UFO sightings are spurious).

Resolution of the Fermi paradox accordingly remains unclear: it may be that intelligent life on Earth is unique in the Galaxy; or it may be that the failure of searches to detect advanced civilisations is subject to so many interpretations as to be, at present, without significance. At some other extreme, it may signal statistically bleak prospects for Earth in terms of impending natural or human-driven catastrophes.

$\gamma$ -ray bursts provide excellent natural ‘synchronisers’ because of their luminosity, occurrence rate, isotropic distribution, large distance, and short duration (Figure 11.47a). A transmitting civilisation propagates a downstream ‘announcement signal’ on registration of a burst, while a searching civilisation (e.g. on Earth) can monitor an upstream target star for a synchronised emitted signal at the time lag set by the additional path length.

Thus a planet-hosting star at  $d = 20$  pc from Earth, and at an angle of  $1^\circ$  from the direction of a burst event seen from Earth, will transmit an event detected 3.63 d later, but whose arrival time can be predicted to  $\pm 1.8$  h. The timing uncertainty

would drop to 60 s in the case of  $10 \mu\text{as}$  Gaia-level parallaxes. A strategy based on observations at opposition, i.e. in the anti-Sun direction, is described by Corbet (2003).

Considering the long time scales of colonisation of even the nearest stars by any advanced civilisation, Anders Johansen (priv. comm., 2014) focused on ‘stepping stone civilisations’ that might bridge the two components of a wide ( $\sim 1000$  au) binary. If these succeeded in maintaining communications with the ‘old world’, such colonisers would generate the maximum ‘spillover’, detectable at Earth, especially in the case of eclipsing systems in the path of the signal beam (Figure 11.47b). Re-

lated considerations are detailed by Pace & Walker (1975). Similar ‘spillover’ configurations might apply in the case of mutual planet–planet transits (§6.14.16) for communications with a multi-planet transiting system (Guillochon & Loeb, 2015).

**Earth’s transit zone** In analogy with transit detection methods, Heller & Pudritz (2016) considered Earth’s ‘transit zone’, viz. the projection of a band around Earth’s ecliptic onto the celestial plane, where distant observers could detect Earth transits across the Sun (Figure 11.47c). Any of the 10 000 GK dwarfs in this zone could identify Earth as habitable and transmit deliberate messages, and accordingly may represent suitable search targets. Wells et al. (2018b) found that the maximum number of transiting solar system planets that could be observed from any given point in the sky is three. For a randomly positioned external observer, there is a 2.5% probability of being able to observe at least one transiting planet, 0.2% for at least two, and 0.03% for three. At present, 68 known exoplanets have a favourable location to observe such transits, and they estimate that there are  $3.2 \pm 1.2$  and  $6.6^{+1.3}_{-0.8}$  (known) temperate Earth-sized planets orbiting GK and M dwarf stars brighter than  $V = 13$  and 16 respectively, that are located in Earth’s transit zone.

Kipping & Teachey (2016) suggested that transit periods provide a window in which observers may communicate. They considered that a civilisation may deliberately broadcast their presence by distorting their transit to an artificial shape, serving as a SETI beacon and a medium for data transmission.

**Messaging (METI)** The general questions surrounding *Active SETI*, or *Messaging to Extraterrestrial Intelligence*, *METI*, remain the subject of some debate (e.g. Haqq-Misra et al., 2012; Musso, 2012; Penny, 2012; Shostak, 2013; Vakoch et al., 2013; Korbitz, 2014; Benford, 2014; Vakoch, 2016). Nonetheless, various intentional (and sometimes controversial) messages have been sent from Earth to space. Developing a specific message is part of the aims of the Breakthrough Message initiative (footnote, page 645).

**METI in practice** Amongst them are some dozen specific interstellar radio messages, including the Morse Message to Venus in 1962, the 3-min Arecibo interstellar radio message of 1974, constructed by Frank Drake and Carl Sagan, and sent to the globular cluster M13, and ‘A Message from Earth’, sent using the RT-70 radar telescope of the Ukraine State Space Agency in 2008 October towards GJ 581 c, which will arrive at its destination early in 2029.

Pioneer 10 and 11 carry Au–Al plaques featuring the human male and female forms along with several symbols providing information about the origin of the spacecraft, in case either is ever found by other intelligent life-forms (Sagan et al., 1972). The Voyager Golden Record was a phonograph recording included on each of the Voyager spacecraft launched in 1977, and containing (along with an enabling stylus) sounds and images portraying the diversity of life and culture on Earth and selected for NASA by a committee chaired by Carl Sagan.

Less intentional are the broadcast radio waves propagating into space for the past 100 yr, since the days of Marconi, and representing an expanding bubble announcing humanity’s presence to any listener. The specific controversy that surrounded the possible dangers of sending out a ‘reply’ signal in the context of the SETI deliberations at the time of the 1967 discovery of pulsars are recounted by Penny (2013).

**Interstellar travel** Notwithstanding prodigious engineering challenges, various concepts for interstellar travel have been considered over the years, notably Projects Daedalus and Icarus (Crawford, 2016, and references). While human transport to the nearest neighbour, Proxima Cen, would take some 100 000 yr using modern chemical thrusters, the ‘Breakthrough Starshot’ initiative has stimulated discussion for a gm-scale spacecraft to reach the  $\alpha$  Cen system in 20–100 yr (e.g. Heller & Hippke, 2017; Heller et al., 2017; Hoang et al., 2017; Kipping, 2017). Ideas include high-power lasers firing at 1 gm solar sails in near-Earth orbit, accelerating to  $v \sim 0.2c$  within minutes. This calls for a  $10^5 \text{ m}^2$  sail with the mass-to-surface ratio of graphene ( $\sim 10^{-6} \text{ kg m}^{-2}$ ), a 10 gm payload, and various shielding strategies. Solar photons may provide adequate acceleration, while deceleration may exploit the stellar photon pressure of the  $\alpha$  Cen triple system combined with gravity assist.

### 11.8.7 Fermi paradox

The *Fermi paradox*, or ‘where is everybody?’, poses a deceptively simple question which, while being somewhat detached from mainstream research, has proven particularly challenging to answer. It attempts to weigh the evidence for and against the existence of other intelligent civilisations (box, page 647).

According to current understanding, there is no evidence at present which contradicts the hypothesis that life arose on Earth due to such extraordinarily improbable events that it is unlikely to have arisen elsewhere within the observable Universe. But the converse is also true: there is no evidence at present which contradicts the hypothesis that life arose on Earth due to such ordinary and probable events that it is likely to have arisen in many other places within the observable Universe.

As the 19th century Scottish essayist Thomas Carlyle remarked on looking at the night sky: ‘*A sad spectacle. If they be inhabited, what a scope for misery and folly. If they be not inhabited, what a waste of space.*’

**Who will speak for Earth?** The public reaction to a SETI discovery, the form of any proposed ‘response’, as well as the possible impact on science and society, all depend on the character of the phenomenon discovered: on the discovery method, on the distance to the source, and on its reliability. The Rio Scale of 2001, and the London Scale of 2011, attempt to quantify the relative importance of such low-probability, high-consequence announcements (Almár, 2011; Gartelle, 2015).

In preparation for any such forthcoming evidence, the International Academy of Astronautics established a ‘Permanent SETI Study Group’ in 2001. Under it, a ‘Post-Detection Task Group’ is mandated to ‘*prepare, reflect on, manage, advise, and consult in preparation for and upon the discovery of a putative signal of extraterrestrial intelligent origin.*’

Evidently, concerns such as ‘who will speak for Earth’ when or if contact is made (Goldsmith, 1988), are some way from today’s scientific mainstream, but perhaps not as far as they were 25 years ago.

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# The solar system

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THEORIES OF THE formation of the solar system have been greatly advanced over the past few decades, in part through a wealth of new and diverse solar system observations from ground and space, including a range of spacecraft fly-bys, orbiters, and landers. These observations have assisted and constrained theories of exoplanet formation and evolution which have, in turn, provided considerable new insights into the various processes which have controlled the solar system's origin and subsequent evolution.

This chapter provides a selective overview of some of the properties of the solar system, and inferences about its origin and evolution, from the vast range of ongoing research (cf. Table 12.1). It focuses on those topics that may be particularly relevant to exoplanet research.

Amongst them are specific properties of the Sun, the orbital motions of the planets (including spacings, eccentricities, inclinations, dynamical stability, and resonances), planetary masses, rotation, angular momentum and obliquities, the existence and properties of planetary satellites and rings, the origin of Earth's Moon and of water on Earth, the occurrence and dynamical features of other minor bodies (comets, asteroids, meteorites, the Edgeworth–Kuiper belt, the Oort cloud, and zodiacal dust), bulk and isotopic compositions, radiogenic isotope ages, cratering records, and the various disruptive events that may have affected the development of life on Earth.

Over the past decade, the growing appreciation of the possible role of planetary migration in the early solar system has provided a substantial advance in understanding of both its inner and outer populations.

## 12.1 The Sun

### 12.1.1 A prototype for exoplanet host stars

All exoplanet detection methods are based on some simplified model of the host star. Required models rapidly become more complex: for photometric transit detection, effects such as limb darkening, spin axis orientation, rotation rate, rotational flattening, differential ro-

tation, the presence of star spots, and stellar oscillations are already relevant. For all detection methods, the many manifestations of stellar activity are frequently a potential limiting source of noise.

The Sun provides a well-studied, if still incompletely understood, prototype for characterising many of these phenomena.<sup>1</sup> Elsewhere in this volume, effects such as limb darkening (§6.14.1), polarisation (§6.17), star spots (§6.14.2), the solar cycle and other manifestations of stellar activity (§6.11.1, §2.4.5), photospheric convection (§2.2.4), differential rotation (§8.3.3), and asteroseismology (§8.6), are described, all building on knowledge derived in large part from the Sun. Although this review will not venture into details of the Sun, a short historical orientation is included (box, page 650).

Of the techniques relevant for understanding the Sun, its internal structure, and its evolution, main sequence modeling is discussed briefly in Section 8.2, and helioseismology/asteroseismology in Section 8.6.

**Observations** Temporal, spatial, and spectral observations, of continually improving quality, are made from dedicated ground-based solar telescopes, including the 0.7-m VTT and the 1.5-m GREGOR Solar Telescope, both at the Teide Observatory. Two future 4-m telescopes promise further advances: the Daniel K. Inouye Solar Telescope (DKIST, formerly ATST, Maui, due for completion in 2018), and the European Solar Telescope (scheduled for construction in the Canary Islands, 2020–25).

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<sup>1</sup>Further reading: Pasachoff (2010) provides a guide to the extensive solar literature, while the 'Living Reviews in Solar Physics' detail the many topics that are potentially relevant to exoplanet work. These include: Local helioseismology (Gizon & Birch, 2005); Star spots (Berdyugina, 2005); The Sun and the Earth's climate (Haigh, 2007); Stellar chromospheric activity (Hall, 2008); Solar interior rotation and its variation (Howe, 2009); Dynamo models of the solar cycle (Charbonneau, 2010); Sun spot modeling (Rempel & Schlichenmaier, 2011); The solar cycle (Hathaway, 2015); Solar and stellar photospheric abundances (Allende Prieto, 2016); Global seismology of the Sun (Basu, 2016); A history of solar activity over millennia (Usoskin, 2017); and Flare observations (Benz, 2017).

**Solar dynamo:** The phenomena collectively known as ‘solar activity’ originate from the cyclic regeneration of the Sun’s large-scale magnetic field. The earliest constraints on an underlying ‘dynamo model’ came from cyclic polarity reversals, and the sun spot butterfly diagram (box, page 213). This chronology of subsequent developments is from Charbonneau (2010).

Observations of sun spots date to the early 17th century, with the discovery of the sun spot cycle in 1843. In the opening decades of the 20th century, the magnetic nature of sun spots and of the solar activity cycle were demonstrated, and George Hale’s polarity laws established the existence of a well-organised toroidal magnetic flux system, residing somewhere in the solar interior, as the source of sun spots. In 1919, Joseph Larmor suggested the inductive action of fluid motions as one of a few possible explanations for the origin of this magnetic field.

In 1933, Thomas Cowling demonstrated that even the most general axisymmetric flows could not sustain an axisymmetric magnetic field against Ohmic dissipation. This problem was only resolved in the 1950s, when Eugene Parker noted that the Coriolis force could impart a systematic cyclonic twist to rising turbulent fluid elements in the convection zone, providing the necessary symmetry breaking. The idea was put on a quantitative basis with the development of mean-field electrodynamics. By the late 1970s, consensus had almost emerged as to the nature of the solar dynamo.

Four further problems then surfaced: (a) because of buoyancy effects, magnetic fields strong enough to produce sun spots could not be stored in the solar convection zone for sufficient time to ensure adequate amplification; (b) simulations of turbulent thermally-driven convection in a thick rotating spherical shell produced magnetic field migration patterns very different to what is observed; (c) the emerging field of helioseismology provided the first determination of internal differential rotation, which turned out markedly different from those effects needed to produce solar-like dynamo solutions in the context of mean-field electrodynamics; (d) the ability of the  $\alpha$ -effect and magnetic diffusivity to operate as assumed in mean-field electrodynamics was also called into question by theoretical calculations and numerical simulations.

Charbonneau (2010) suggests that ‘*while a near-consensus exists in ascribing the magnetic cycle to the inductive action of fluid motions pervading the interior, nothing remotely resembling consensus currently exists as to the mode of operation of the solar dynamo*’. Most dynamo models of the solar cycle rely heavily on numerical solutions of the partial differential equations of magnetohydrodynamics. For further details, the review by Charbonneau (2010) provides an authoritative entry point, with the Babcock–Leighton mechanism (Babcock, 1961) still providing a useful context.

Amongst many solar and heliospheric space missions since the 1960s, some of the more recent dedicated to solar observations include JAXA’s Yohkoh (formerly Solar-A, operational 1991–2005); Solar and Heliospheric Observatory (SOHO, observing from L1 since 1996); NASA’s TRACE (Transition Region and Coronal Explorer, operational 1998–2010); RHESSI (formerly HESSI, observing solar flares since 2002); JAXA’s Hinode (formerly Solar-B, in sun-synchronous orbit since 2006); NASA’s STEREO (operational since 2006), and Solar Dynamics Observatory (SDO, in geosynchronous orbit since 2010; Pesnell et al. 2012). NASA’s Parker Solar Probe (previously Solar Probe, and Solar Probe Plus, approaching to  $8.5R_{\odot}$  to probe the corona) is scheduled for launch in mid-2018. ESA’s Solar Orbiter, or SoLo (approaching to  $60R_{\odot}$ ) is scheduled for launch in early 2019.

**Sun spots** Sun spots appear when deep-seated toroidal flux ‘ropes’ rise through the convective envelope, and emerge at the photosphere. The limited understanding of the process by which the large-scale solar magnetic field produces the concentrated toroidal flux ropes that, through buoyant destabilisation, give rise to sun spots, is described by Charbonneau (2010) as perhaps ‘*the most severe missing link between dynamo models and solar magnetic field observations*’.

Assuming that the flux ropes are formed where the magnetic field is the strongest, and rise radially to the surface, the sun spot butterfly diagram (box, page 213) is a spatio-temporal map of the Sun’s internal, large-scale toroidal magnetic field component. Amongst detailed models, those of Rempel (2012) are widely invoked.

### 12.1.2 Birth in a cluster

Most stars are born in molecular clouds as members of stellar clusters although, rarely, some may be born in isolation (Lada & Lada, 2003). Whether the Sun was formed in isolation or in a cluster remains uncertain (Adams, 2010; Dukes & Krumholz, 2012), although Adams (2010) concluded that it was probably formed in a cluster of  $10^3 - 10^4$  stars.

**Evidence** Evidence for a cluster origin includes (Pfalzner, 2013):

(a) a relatively sharp outer boundary of the planetary system at  $\leq 30$  au, with the Edgeworth–Kuiper belt at  $\geq 45$  au containing only  $\sim 0.01-0.1M_{\oplus}$  (Bernstein et al., 2004). The protoplanetary disk from which the solar system formed was most likely considerably larger at the time of planet formation. Processes that could have led to disk truncation, all augmented by a relatively dense stellar environment, include gravitational interactions with other cluster members (Ida et al., 2000; Kobayashi & Ida, 2001; Pfalzner et al., 2005; Kenyon & Bromley, 2004b; Spurzem et al., 2009), photoevaporation by nearby massive stars (Adams et al., 2006; Owen et al., 2010; Mitchell & Stewart, 2011), or a supernova explosion (Chevalier, 2000);

(b) the typically higher eccentricities and inclinations of the Kuiper belt objects has been taken as evidence of an encounter. The most prominent example is Sedna (§12.5.8; Gomes et al., 2005a). One explanation for these high eccentricities is some type of dynamical interaction, either a close encounter (Morbidelli & Levison, 2004), a wide-binary solar companion (Matese et al., 2005), or as a result of the Sun’s Galactic migration (Kaib et al., 2011c; Martínez-Barbosa et al., 2017). Such an encounter would have occurred early in the solar system’s history, when the stellar density was relatively high, otherwise leading to planetary orbit perturbations, comet stripping, and instabilities of the inner Oort cloud (Gaidos, 1995; Adams & Laughlin, 2001; Pfalzner, 2013);

Table 12.1: Selected solar system publications in the University of Arizona Space Science Series, ordered by publication date.

Title	Reference
Jupiter	Gehrels (1976)
Satellites of Jupiter	Morrison (1982)
Planetary Rings	Greenberg et al. (1984)
Saturn	Gehrels et al. (1984)
Satellites	Burns & Matthews (1986)
Mercury	Vilas et al. (1988)
Planetary & Satellite Atmospheres	Atreya et al. (1989)
Uranus	Bergstralh et al. (1991)
Solar Interior and Atmosphere	Cox et al. (1991)
The Sun in Time	Sonett et al. (1991)
Mars	Kieffer et al. (1992)
Neptune and Triton	Cruikshank et al. (1995)
Venus II	Bougher et al. (1997)
Pluto and Charon	Stern & Tholen (1997)
Origin of the Earth and Moon	Canup & Righter (2000)
Comets II	Festou et al. (2004)
Meteorites... II	Lauretta et al. (2006)
Solar System beyond Neptune	Barucci et al. (2008a)
Protostars and Planets VI	Beuther et al. (2014)
Asteroids IV	Michel et al. (2015)

(c) short-lived radionuclides ( $^{60}\text{Fe}$  and  $^{26}\text{Al}$ ) and their decay products, formed in the protosolar nebula and preserved in meteorites (Hester et al., 2004; Hester & Desch, 2005; Gounelle & Meibom, 2008; Boss, 2011a; Makide et al., 2011; Boss, 2012b). This is perhaps explained by a type II supernova within 1–2 pc of the young Sun (e.g. Looney et al., 2006; Adams, 2010; Dauphas & Chaussidon, 2011; Gritschneider et al., 2012; Boss & Keiser, 2014). A different interpretation, ascribed to igneous differentiation and supported by evidence of extrasolar asteroids inferred from white dwarf photospheres (§8.9.5), has also been proposed (Jura et al., 2013).

Other evidence includes the solar obliquity (§12.1.5) which, according to its origin, *may* hint at a high density birth environment (Gaidos, 1995), and the presence of the Oort cloud (§12.5.7), suggestive of enhanced gravitational binding at the earliest epochs (Fernández, 1997).

**Siblings, twins and analogues** A hypothetical star born in the same cluster, and therefore sharing the Sun's age, chemistry, and Galactic kinematics, is termed a *solar sibling*. No unambiguous siblings are known (§8.5.2). Nor is the significance to life on Earth of the Sun's apparent nature as a *singleton*, viz. a single star which has never spent time within a binary system, nor suffered close (sub-100 au) encounters with other stars (Davies et al., 2008; Parker et al., 2014).

Solar twins and solar analogues (viz., stars 'like the Sun', but not necessarily from the same birth cluster), and solar siblings, are considered in Section 8.5.2.

**The Local Bubble and nearby supernovae** The Sun is traveling through the *Local Interstellar Cloud*, a density enhancement in a lower density 'cavity' in the interstellar medium known as the *Local Bubble*, in which the neutral-H density of about  $0.05 \text{ atoms cm}^{-3}$  is one tenth the average of the Galaxy's interstellar medium (e.g. Maíz-Apellániz, 2001; Lallement et al., 2003).

The cavity, the sparse hot X-ray emitting gas within it, and the layered deposition of  $^{60}\text{Fe}$  on Earth (e.g. Knie et al., 1999; Wallner et al., 2016) and the Moon (Fimiani et al., 2016), are generally attributed to nearby ( $\sim 100 \text{ pc}$ ) supernovae within the past 10–20 Myr. Most recent studies suggest two main events, at 6.5–8.7 Ma and 1.7–3.2 Ma (Breitschwerdt et al., 2016).

There has long been speculation, from biostratigraphy, that terrestrial mass extinctions might be related to supernovae, although there is no definitive association (e.g. Schindewolf, 1954; Bambach, 2006; Melott & Thomas, 2009; Melott & Bambach, 2014). Models of both prompt photons and cosmic rays suggest that a very nearby event ( $\lesssim 8 \text{ pc}$ ) is necessary for a *major* extinction (Gehrels et al., 2003). Studies have also considered climate changes and mutation rates due to visible light, ozone depletion, prolonged tropospheric ionisation, and muon irradiation (Thomas et al., 2016).

### 12.1.3 Solar nebula abundances

The products of the thermochemical equilibrium processes described in §11.2.2 are sensitive to the initial elemental composition of the gas. To infer the gas and mineralogical composition of the solar nebula out of which the solar system planets formed, therefore requires an accurate estimate of its initial elemental abundances.

Such estimates can be made from a combination of solar photospheric and meteoritic abundances. It needs to address the extent to which observed solar photospheric abundances reflect the Sun's bulk composition, and the extent to which the latter, and the wide variety of observed meteoritic compositions, properly reflect the conditions in the original solar nebula.

**Detailed estimates** Elemental photospheric and meteoritic abundances published by Anders & Grevesse (1989) are still widely referenced, although various revisions in abundances have since been proposed (e.g. Grevesse & Noels, 1993; Grevesse et al., 1996; Grevesse & Sauval, 1998, 2002). In these cited works, the abundances derived from photospheric and meteoritic data are generally taken as representative of the bulk solar system composition.<sup>2</sup>

For meteorite abundances, the small class of CI (Ivuna type) carbonaceous chondrites lack chondrules and refractory inclusions, have the most 'primitive' compositions (essentially identical to that of the Sun, excluding gaseous elements like H and He), and are therefore used as a standard for assessing the degree of chemical fractionation experienced by materials formed throughout the solar system. Significant importance has been given to the 14 kg Orgueil meteorite, the most massive of the CI chondrites, which fell in France in 1864.

<sup>2</sup> On the logarithmic astronomical scale, the numerical abundance of element 'x' is designated  $A(x) = \log e(x)$ . On this scale, the number of H atoms is set to  $A(\text{H}) = \log n(\text{H}) = 12$ , so that  $A(x) = \log[n(x)/n(\text{H})] + 12$ . On the cosmochemical scale, abundances, designated as  $N(x)$ , are normalised to the number of silicon atoms of  $N(\text{Si}) = 10^6$ .

Abundances determined from the Sun's photospheric spectrum and from CI-type meteorites agree reasonably well (Anders & Grevesse, 1989), but there are differences. Compared to the solar photosphere, CI-meteorites are depleted in noble gases, and in H, C, N, and O which readily form gaseous compounds, while they are enriched in elements processed in the Sun (notably Li). Taking account of such caveats, the usually more precise analyses of CI chondrites can then be used to refine photospheric abundances, preferably based on the mean composition of the CI group (Lodders, 2003).

Estimates of present solar system abundances have also been further revised as a result of improved understanding of various physical processes. Models of the Sun's evolution and interior show that observed photospheric abundances (relative to H) are lower than those of the proto-Sun, because He and other heavy elements have settled toward the Sun's interior over its evolutionary lifetime (e.g. Pinsonneault, 1997; Talon, 2008).

Allende Prieto et al. (2001, 2002) presented downward revisions of the solar abundances of oxygen and carbon, partly from detailed models of solar granulation, and partly by accounting for departures from local thermodynamical equilibrium. This is important because these two abundant elements govern much of the chemistry of other less abundant elements. A lower absolute oxygen abundance lowers the condensation temperatures of O-bearing compounds, while the C/O ratio further influences many condensation temperatures.

**Reference abundances** Lodders (2003) gives a reference set of photospheric and protosolar abundances, derived from solar and meteoritic abundances: her Table 1 gives photospheric and meteoritic abundances for all 83 naturally occurring elements; Table 2 gives corresponding solar system abundances, i.e. the inferred protosolar values, unfractionated with respect to H; Table 6 gives solar system isotopic abundances.

#### 12.1.4 Age and early chronology

The Sun's age is loosely defined as the time elapsed since it arrived on the *zero-age main sequence*. This in turn may be defined as the time when nuclear reactions just began to dominate gravitation as the primary energy source. It is estimated from helioseismology studies to be  $4.57 \pm 0.11$  Ga (Guenther & Demarque, 1997; Dziembowski et al., 1999; Bonanno et al., 2002). The same value,  $4.57 \pm 0.07$  Ga, was derived from meteoritic dating by Bahcall et al. (1995), although they stated that '*... at what stage of solar evolution this narrow time band represents is not obvious*'.

**Event dating** Absolute ages, primarily from the coupled U–Pb decay routes, and relative ages, based on the  $^{26}\text{Al} \rightarrow ^{26}\text{Mg}$  and  $^{182}\text{Hf} \rightarrow ^{182}\text{W}$  chronometers and others, are providing a reliable and consistent sequence of timings for events in the early solar system deduced from the meteoritic records (Figure 10.2).

The mm to cm-sized refractory calcium–aluminum–rich inclusions in chondritic meteorites are believed to have been the earliest solids to form, with absolute U–Pb dating indicating formation at  $4567.2 \pm 0.7$  Ma (Allègre et al., 1995; Amelin, 2006; Amelin & Krot, 2007; Wadhwa et al., 2007). Thereafter, relative dating indicates that an interval of up to 3 Myr preceded the formation of the chondrules (Allègre et al., 1995; Amelin et al., 2002; Kita et al., 2005), while the parent bodies of iron meteorites may have formed just after, or a little before, the chondrules (Kleine et al., 2002).

**Present chemical inventory:** Present knowledge of the chemical composition of solar system material accessible to analysis can be summarised by quoting the abstract of Palme & Zipfel (2017) largely verbatim.

In the Sun the three most important rock forming elements Mg, Si and Fe have about the same number of atoms ( $\text{Mg}/\text{Si} = 1$ ;  $\text{Fe}/\text{Si} = 0.91$ ); the number of Al atoms is a factor 10 lower ( $\text{Al}/\text{Si} = 0.09$ ). Chondritic meteorites have essentially the same chemical signature with some variability, about 20% for Mg/Si, 50% for Al/Si and a factor two for Fe/Si. These variations can be accounted for by variably mixing components formed by condensation in a cooling gas of solar composition (Mg-silicates, Ca-Al-rich inclusions, NiFe metal). The bulk Earth composition is within this range, and may be broadly considered chondritic.

The bulk compositions of the other terrestrial planets are less well known. They all have a metal core and basaltic surface rocks. Exceptions are Mercury with too much and the Moon with too little iron for a chondritic bulk composition. Asteroids also seem to have chondritic bulk compositions. S-type asteroids have been confirmed to be the parent bodies of ordinary chondrites. Most of the C-type asteroids appear to represent carbonaceous chondrites.

The mm to sub-mm sized micrometeorites are debris of asteroids and/or comets. They are largely chondritic in composition but the ratio of cometary to asteroidal material is unclear. If there is a significant fraction of cometary material, comets should have chondritic bulk composition, as approximately inferred from the Giotto data.

Interplanetary dust particles,  $\mu\text{m}$ -sub- $\mu\text{m}$  in size are also largely chondritic. They often contain GEMS (glass with embedded metal and sulphides), nm-sized particles which scatter around chondritic bulk compositions and are considered by some to be undisturbed interstellar material, the parental material of the solar system. If material left over from the formation of the Sun was CI-chondritic with respect to rock forming elements, then massive redistribution of high temperature components must have occurred in the early solar nebula to account for the enrichment of refractory elements in the Earth.

Similar dating efforts have been reported for meteoritic events (e.g. Kleine et al., 2005a; Scott, 2007; Chambers et al., 2010), the differentiation histories of Earth (e.g. Kleine et al., 2002, 2004b; Yin et al., 2002; Halliday, 2004), Mars (e.g. Borg & Drake, 2005; Nimmo & Kleine, 2007), and the Moon (e.g. Kleine et al., 2005b; Touboul et al., 2007, 2009), the formation of Earth's atmosphere (Allègre et al., 1995; Halliday, 2004), and the spatial heterogeneity of short-lived radionuclides (Boss, 2007a).

**Age of the Earth** Attempts to estimate the age of the Earth itself has a long history (Dalrymple, 1991). Central to more recent contributions, zircon ( $\text{ZrSiO}_4$ ) from Jack Hills in W. Australia yields U–Pb ages up to 4.404 Ga (box, page 653), making them the oldest minerals dated on Earth (Wilde et al., 2001). The age of the Earth, corresponding to the end of its accretion, early differentiation, core formation, and atmospheric outgassing is, as a result, dated at some 100 Myr after the formation of the first meteorites (Allègre et al., 1995; Valley et al., 2014).

**Transient heating events** One of the factors underlying acceptance of the solar nebular theory in the 1970s



**Geochronology:** *Geochronology*, the scientific determination of absolute and relative ages of the geological record, exploits a variety of radiometric (and stratigraphic) dating techniques, generally based on comparison between the observed abundance of a naturally occurring radioactive isotope (or *radionuclide*) and its decay or daughter products (referred to as *radiogenic nuclides*, whether they are stable or not), using known decay rates (e.g. Dickin, 2005).

One of the oldest and most refined methods is the uranium–lead scheme, used for one of the earliest accurate estimates of the age of the Earth (Patterson, 1956). It achieves a precision of  $\sim 1$  Myr in *absolute ages* over the entire geological record. In its most general form, it exploits the two parallel U–Pb decay routes:  $^{238}\text{U} \rightarrow ^{206}\text{Pb}$  ( $t_{0.5} \sim 4.5$  Gyr) and  $^{235}\text{U} \rightarrow ^{207}\text{Pb}$  ( $t_{0.5} \sim 0.7$  Gyr) to determine two independent ‘concordant’ ages. Discrepancies in the two estimates provides constraints on sample contamination or radiogenic loss. The U–Pb isochron dating variant uses a single decay route, usually  $^{238}\text{U} \rightarrow ^{206}\text{Pb}$ , while the Pb isotope or lead–lead dating method makes use of the Pb isotope ratios alone.

The method is frequently applied to the mineral zircon ( $\text{ZrSiO}_4$ ), which incorporates U into its crystalline structure but strongly rejects Pb, such that the entire measured lead content is considered to be of radiogenic origin.

Such absolute radiometric dating requires a measurable fraction of the parent radionuclide to remain in the sample. For bodies dating back to the beginning of the solar system, this requires extremely long-lived parent isotopes, which in turn implies that the derived absolute ages are inevitably imprecise.

Accurate *relative ages* can be determined from the decay products of short-lived isotopes that are themselves no longer present. From their measured decay products, it is inferred that various short-lived radionuclides, including  $^{10}\text{Be}$ ,  $^{26}\text{Al}$ ,  $^{53}\text{Mn}$ ,  $^{60}\text{Fe}$ ,  $^{129}\text{I}$  and  $^{182}\text{Hf}$ , were injected into the early solar nebula, possibly from a supernova explosion (e.g. Meyer & Zinner, 2006; Bizzarro et al., 2007).

The  $^{26}\text{Al} \rightarrow ^{26}\text{Mg}$  chronometer is widely used to estimate the relative ages of chondrules. With  $t_{0.5} \sim 720\,000$  yr, the parent nuclide is no longer extant, and dating exploits the deviation from the natural abundance of  $^{26}\text{Mg}$  in comparison with the ratio of the stable isotopes  $^{27}\text{Al}$  and  $^{24}\text{Mg}$  (e.g. Krot et al., 2005b). Relative ages can be similarly estimated from the (short-lived decay) chronometers  $^{53}\text{Mn} \rightarrow ^{53}\text{Cr}$ ,  $^{60}\text{Fe} \rightarrow ^{60}\text{Ni}$ , and  $^{182}\text{Hf} \rightarrow ^{182}\text{W}$ .

was the realisation that many meteoritic features could be understood in terms of their condensation from a hot vapour. The first theoretical studies of the condensation of material of solar system composition were published at around that time (e.g. Larimer, 1967; Grossman, 1972), and these reinforced the idea that material in the early solar system had been in a hot gaseous form. However, as concluded and emphasised by Cameron (1978b) ‘*At no time, anywhere in the solar nebula, anywhere outwards from the orbit of Mercury, is the temperature in the unperturbed solar nebula ever high enough to evaporate completely the solid materials contained in interstellar grains.*’

Nevertheless, as deduced from meteoritic crystalline silicates, both chondrules and refractory inclusions (calcium–aluminum–rich inclusions, or CAIs), some form of intense and repeated transient heating must have been important in the early solar system. Such heating is not part of the current models for planetary system formation, and the origin of these high-temperature products, and their precise chronology, has been the subject of prolonged investigation (e.g. Boss, 1996a; Shu et al., 1996; Rubin, 2000; Jones et al., 2000b; Ghosh et al., 2004; Sanders & Taylor, 2005; Krot et al., 2005a; Connolly et al., 2006; Lauretta et al., 2006; Scott, 2007; Wooden et al., 2007; Apai et al., 2010).

**Contenders** While the heating mechanism remains unknown, contenders are plentiful, amongst them lightning-type discharges caused by solar nebula turbulence (Cameron, 1966; Whipple, 1966; Pilipp et al., 1992, 1998; Love et al., 1995; Desch & Cuzzi, 2000), the hypothetical X-wind from an early active Sun (Shu et al., 1996, 1997, 2000; Shu, 2001), the decay of  $^{26}\text{Al}$  and other short-lived radionuclides (Bennett & McSween, 1996), and in particular the resulting lightning-induced flash heating of dust and pebbles driven by positron release from the  $^{26}\text{Al}$  decay (Johansen & Okuzumi, 2018), shock waves (Ciesla & Hood, 2002; Desch & Connolly, 2002; Boss & Durisen, 2005; Desch et al., 2005; Hood & Weidenschilling, 2012), X-ray flares (Feigelson & Montmerle, 1999; Joung et al., 2004; Nakamoto et al., 2005),  $\gamma$ -ray bursts and associated discharges (McBreen & Hanlon, 1999; Duggan et al., 2003; McBreen et al., 2005), giant impact heating by partially molten planetesimals (Hutchison & Graham, 1975; Hutchison et al., 1988; Rubin, 1995; Sanders & Taylor, 2005; Krot et al., 2005a; Sanders & Scott, 2012), and short circuits in magnetorotational instabilities (Hubbard et al., 2012; Connolly et al., 2012; McNally et al., 2013).

Chronologies from U-corrected Pb–Pb dating yield absolute ages of individual CAIs and chondrules from primitive meteorites. Connolly et al. (2012) found that CAIs define a brief formation interval corresponding to an age of  $4567.30 \pm 0.16$  Myr, whereas chondrule ages range from  $4567.32 \pm 0.42$  to  $4564.71 \pm 0.30$  Myr, contrasting with the long-held view of an age gap between CAIs and chondrules (§12.1.4), and suggesting that chondrule formation may have started contemporaneously with CAIs, and lasted  $\sim 3$  Myr. This time scale is similar to those inferred for disk lifetimes, hinting that the formation of CAIs and chondrules reflects a process intrinsic to the secular evolution of protoplanetary disks.

A recent addition to the list of possible transient heating mechanisms, and one tying in to this conjecture, can be found in the spike in impact velocities seen in numerical simulations of protoplanetary disk migration hypothesised early in the formation of the solar system, as a consequence of the ‘Grand Tack’ hypothesis. This is described further in Section 12.6.4.

### 12.1.5 Solar obliquity

The *solar obliquity*, i.e. tilt of its rotation axis, is  $7^\circ$  with respect to the mean planetary orbital plane, and  $6^\circ$  with respect to the total angular momentum, or *invariable plane*. There is no definitive explanation for this significant axial tilt.

**Hypotheses** The effects of inhomogeneous infall on the obliquities of the (outer) planets (§12.4.6) may also account for the

solar obliquity (Tremaine, 1991). With a similar premise of turbulent and chaotic infall, especially if truncated by stellar encounters, significant misalignment between the final stellar rotation axis and disk spin axis was also found by Bate et al. (2010a).

The suggested existence of Planet Nine (§12.5.8) may offer an alternative explanation. Gomes et al. (2017) showed that the motion of the giant planets can be decomposed into a classical component relative to their own invariable plane, combined with a slow precession of that plane relative to the total angular momentum of the solar system, including Planet Nine. For specific properties of Planet Nine, this precession may explain the presently-observed solar obliquity (Bailey et al., 2016; Lai, 2016; Gomes et al., 2017). A somewhat analogous but more extreme situation may exist for the two inner, co-planar but misaligned, planets in the Kepler-56 system (Gratia & Fabrycky, 2017).

More generally, but presumably not relevant for the Sun, misaligned orbits can result from disk migration in binary systems whose orbital plane is uncorrelated with the individual stellar spin axes (Batygin, 2012; Matsakos & Königl, 2017), or in high-eccentricity migration involving Lidov-Kozai oscillations (e.g. Storch et al., 2017). There is a small possibility that a distant, undetected, brown dwarf companion remains gravitationally bound to the Sun, or that a formerly wide companion was lost during one of its 150 or so Galactic plane crossings.

The non-zero obliquity could also result from a stellar encounter shortly after the solar system formation, leading to a tilt of the circumstellar disk with respect to the rotation axis of the central star (Heller, 1993). In a related explanation, Wijnen et al. (2017a) suggested that it could have originated through interaction between the protoplanetary disk and supernova ejecta.

Finally, the Sun is assumed to rotate about a single axis. While the axis of rotation of the photospheric layers is well determined, it cannot be excluded *a priori* that the direction could vary as a function of radius. Constraints on a possible oblique rotation of the core are available from low-degree pulsation modes in SOHO-LOI data (Gizon et al., 1998). Hints of two different rotation axes inside the star KIC-10195926 have, for example, been identified (Kurtz et al., 2011).

### 12.1.6 Dynamical aspects

**Galactic plane passages** The Sun is a very typical thin-disk star (e.g. Fuhrmann, 2004). It has a small peculiar velocity with respect to the Local Standard of Rest, and its low relative  $U$  and  $V$  velocities (§3.4.7) decrease its collision probability while crossing the Galactic plane. Its typical  $W$  velocity, in contrast, minimises its mid-plane crossing time and hence minimises encounters, enhancing the environmental stability for the orbiting planets. Estimates of the most recent mid-plane crossing time relies on values of  $Z_0 \approx 8 - 27$  pc and  $W_0 \approx 7$  km s<sup>-1</sup>, away from the plane, i.e. between 1–4 Ma. Previous and future passages require knowledge of the Sun's vertical oscillation period, generally considered to be around 60–85 Myr (e.g. Bienaymé, 1999).

More generally, globally disruptive events include asteroid/comet impacts, large igneous provinces, and glaciations (§12.3.9). All may have contributed to mass extinctions, leaving imprints in fossil diversity and environmental data. An understanding of the relationship

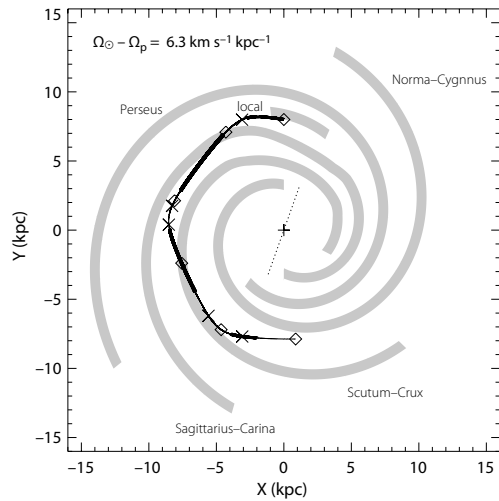


Figure 12.1: The Galaxy's spiral arms showing the four main arms plus the local (Orion) spur (shaded), the Galactic centre (+), and the central bar (dotted). The solid line shows the Sun's path in the spiral arm reference frame for  $\Omega_p = 14.4$  km s<sup>-1</sup> kpc<sup>-1</sup>. Thick lines delineate icehouse epochs, × indicate large mass extinctions, and diamonds indicate 100 Myr intervals from the present (topmost symbol). From Gies & Helsel (2005, Figure 2), by permission of IOP Publishing/AAS.

between the timings of the largest extinctions, and their potential proximal causes, nonetheless remains elusive.

Svensmark (2006b) used  $\delta^{18}\text{O}$  proxy data from the Phanerozoic database over the last 500 Myr, isolating a 140 Myr period identified with the Sun's passage through the spiral arms, and a 30 Myr period which could be related to the crossing of the Galactic plane through the vertical oscillatory motion.

Later work has brought arguments for and against such a correlation (e.g. Bailer-Jones, 2009, 2011; Bailer-Jones & Feng, 2013; Feng & Bailer-Jones, 2014; Rampino, 2015; Rampino & Caldeira, 2015; Gillman & Erenler, 2017; Meier & Holm-Alwmark, 2017).

The Sun's orbital motion may also have been responsible for periods of increased numbers of nearby star passages, in turn triggering increased impact cratering and possibly mass extinctions evident in paleontological records on Earth (e.g. Stothers, 1998; Jetsu & Pelt, 2000, and references therein). The Sun's radial orbital oscillations with an epicyclic period of around 170 Myr should similarly imply minimum impact rates at apogalacticon.

**Passage through Galactic spiral arms** Since its formation ~4.5 Ga, the Sun has made about 20 Galactic orbits ( $P_{\text{orb}} \sim 250$  Myr), with many passages through spiral arms. Terrestrial fossil records show that the rise in biodiversity since the Precambrian has been punctuated by large extinctions, at intervals of 40–140 Myr, representing extremes over a background of smaller events and the natural process of species extinction. Leitch & Va-

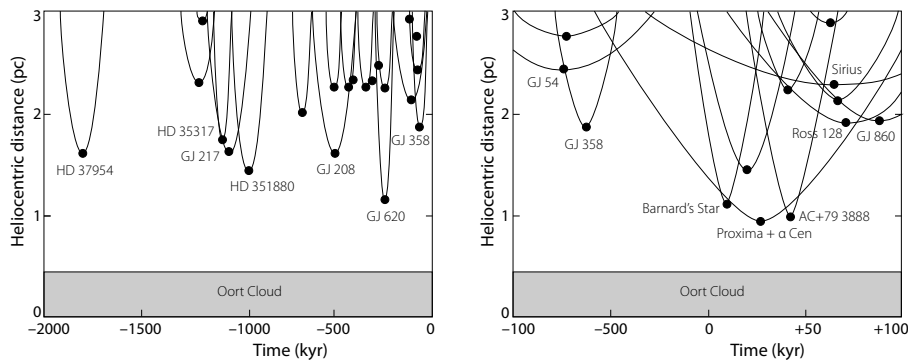


Figure 12.2: Closest predicted stellar passages (a) within the past 2 Myr; (b) for  $\pm 10^5$  yr. Error bars (for time and closest approach) have been omitted. Several close passages are predicted over the next tens of thousands of years. From García-Sánchez et al. (1999, Figures 4 and 6), by permission of IOP Publishing/AAS.

sicht (1998) pointed out that non-terrestrial phenomena proposed to explain these events, such as boloidal impacts and supernovae, are more effective during the solar system's passage through the spiral arms.

Various authors have further argued that there is a correlation between extended 'icehouse' periods on Earth (box, page 676) and its exposure to a varying cosmic ray flux, modulated as the Sun moves through Galactic spiral arms, where enhanced star formation and increased supernova rates create more intense exposure to cosmic rays, and perhaps changes in the chemistry of the upper atmosphere. The proposed driving mechanism is that the cosmic ray flux affects atmospheric ionisation and, in turn, the formation of charged aerosols that promote cloud condensation (e.g. Frakes et al., 1992; Marsh & Svensmark, 2000; Shaviv, 2002, 2003; Yeghikyan & Fahr, 2004a,b; Gies & Helsel, 2005; Svensmark, 2006a,b, 2007; Filipovic et al., 2013).

**Detailed models** Gies & Helsel (2005) found that the Sun's motion is consistent with icehouse epochs occurring around the times of spiral arm passages if the spiral pattern speed is close to  $\Omega_p = 14 - 17 \text{ km s}^{-1} \text{ kpc}^{-1}$ . For  $\Omega_\odot - \Omega_p = 11.9 \pm 0.7 \text{ km s}^{-1} \text{ kpc}^{-1}$ , the Sun would have traversed four spiral arms (e.g. Hou & Han, 2014; Vallée, 2014a,b), at times that correspond with long-duration cold periods on Earth (Figure 12.1). Analyses have been extended by Filipovic et al. (2013).

The influence of cosmic rays on long-term glaciation has been challenged, specifically being considered as secondary compared with changes in atmospheric  $\text{CO}_2$  and oceanic pH (e.g. Royer et al., 2004; Rahmstorf et al., 2004; Sloan & Wolfendale, 2013). Over centuries, solar effects on the Earth's climate are generally attributed to the changing solar magnetic field, but the breakdown according to cosmic ray effects, total solar irradiance, and ultraviolet irradiance remains unclear (e.g. Lockwood, 2006; Gray et al., 2010; Lockwood, 2012).

**Passage of nearby stars or 'fly-bys'** The mean-free collision time between the Sun and other stars in the solar neighbourhood is of order  $10^{13}$  years, very much longer than the age of the Galaxy. Stars in the solar neighbour-

hood therefore behave essentially as a collisionless gas. Nonetheless, measurable effects on Earth due to nearby star passages, in the past or future, may occur.

Close approaches of stars to the solar system may perturb the Oort cloud (e.g. Frogel & Gould, 1998; García-Sánchez et al., 1999; Serafin & Grothues, 2002; Collins & Sari, 2010), with possibly consequences for an increased impact hazard on Earth (Bailer-Jones, 2011; Feng & Bailer-Jones, 2014, 2015; Bailer-Jones, 2015).

**Detailed studies** Various studies have been made, extending over the past and future, and making use of distances and space motions from Hipparcos combined with radial velocities (Matthews, 1994; Mülläri & Orlov, 1996; García-Sánchez et al., 1999; García-Sánchez, 2000; García-Sánchez et al., 2001; Jiménez-Torres et al., 2011; Dybczyński & Berski, 2015; Mamajek et al., 2015a; Crifo et al., 2017). First considerations from Gaia DR1 astrometry are detailed by Bailer-Jones (2018).

The closest known past encounter was the low-mass binary WISE J0720-0846 (Scholz's star), at  $52 \pm 20 \text{ kau}$  ( $0.25 \pm 0.1 \text{ pc}$ , i.e. within the outer Oort cloud) some 70 000 yr ago (Mamajek et al., 2015a). Tracing back the orbit of the Sun, Martínez-Barbosa et al. (2017) estimated a rate of encounters, within 400 kau of the Sun, in the range  $21-63 \text{ Myr}^{-1}$ .

Of future perturbers, GJ 710 has a predicted closest approach of  $< 100 \text{ kau}$  ( $\lesssim 0.5 \text{ pc}$ ), which will result in a minor shower with  $\sim 4 \times 10^{-7}$  of the Oort cloud population being thrown into Earth-crossing orbits (García-Sánchez et al., 2001; Jiménez-Torres et al., 2011; Berski & Dybczyński, 2016; Bobylev & Bajkova, 2017). Gaia DR1 astrometry updates the closest approach to  $\sim 16 \text{ kau}$  (Bailer-Jones, 2018).

Several others come within  $\sim 1 \text{ pc}$  over  $\pm 8.5 \text{ Myr}$ . Gaia will find many new perturbers, including nearby M dwarfs with low tangential velocities (Rickman et al., 2012; Mamajek et al., 2015a; Bobylev & Bajkova, 2017; Bailer-Jones, 2018).

Portegies Zwart & Jílková (2015) introduced the concept of the 'parking zone', defined as the region in the plane of semi-major axis and eccentricity of objects orbiting the Sun that have been perturbed by the Sun's birth star cluster, but not by the planets or the Galactic tidal field. Such orbits maintain a record of the interaction of the solar system with stars of the Sun's birth cluster (Jílková et al., 2015). Martínez-Barbosa et al. (2017) estimate the outer edge of the parking zone at  $a \sim 250 - 1300 \text{ au}$ .

**Planetary influence on solar activity** Solar axial rotation is central to the two main hypotheses for a mechanism underlying the solar cycle: attributed to a turbulent dynamo operating in or below the convection envelope, or to a large-scale oscillation superimposed on a fossil magnetic field in the radiative core.

However, the precise dynamo nature, and many details of the associated solar activity (such as the details of the sun spot cycles, or the prolonged Maunder-type solar minima) remain unexplained (e.g. Choudhuri, 2007; Weiss & Thompson, 2009; Charbonneau, 2010; Jones et al., 2010a), although certain features may arise naturally in some models (e.g. Charbonneau et al., 2007b).

Empirical investigations have long hypothesised an unexplained link between the Sun's barycentric motion and various solar variability indices (e.g. Wolf, 1859; Brown, 1900; Schuster, 1911; Jose, 1965; Ferris, 1969; Tattersall, 2013; Sidorenkov & Wilson, 2017). An example is shown in Figure 12.3.

**Hypothesised causalities** Specifically, acceleration in the Sun's motion, or the change of its orbital angular momentum, have been linked empirically to phenomena such as the Wolf sun spot number counts (Wood & Wood, 1965), climatic changes (Mörth & Schlamming, 1979; Scafetta, 2010), the 80–90-yr secular Gleissberg cycles (Landscheidt, 1981, 1999), the prolonged Maunder-type solar minima (Fairbridge & Shirley, 1987; Charvátová, 1990, 2000; Cionco & Compagnucci, 2012), short-term variations in solar luminosity (Sperber et al., 1990), sun spot extrema (Landscheidt, 1999), the 2400-yr cycle in  $^{14}\text{C}$  tree-ring proxies (Charvátová, 2000), hemispheric sun spot asymmetries (Juckett, 2000; Seker, 2013), torsional oscillations in long-term sun spot clustering (Juckett, 2003), violations of the Gnevishév–Ohl sun spot rule (Javaraiah, 2005), cosmogenic radionuclide correlations over 9400 yr (Abreu et al., 2012; Tattersall, 2013; McCracken et al., 2014), although contested by Cameron & Schüssler (2013) and by Cauquoin et al. (2014), variations in total solar irradiance since 1978 (Scafetta & Willson, 2013), and strong planetary-like cycles at 2.8 GHz (Tan & Cheng, 2013). Claimed effects extend to dust storms on Mars (Shirley, 2015), and river discharges (Cionco & Abuin, 2016).

**Retrograde barycentric motion** A specific curiosity of the Sun's barycentric motion is evident in Figure 3.3a. Around 1990 (and before that, in 1811 and 1632) the Sun had a retrograde barycentric motion, i.e. its angular momentum with respect to the centre of mass was negative (Jose, 1965). Javaraiah (2005) has argued that epochs violating the Gnevishév–Ohl 'sun spot rule', which states that the sum of sun spot numbers over an odd-numbered cycle exceeds that of its preceding even-numbered cycle (Gnevishév & Ohl, 1948; Komitov & Bonev, 2001; Nagovitsyn et al., 2009; Zolotova & Ponyavin, 2015), are close to these intervals of the Sun's retrograde motion.

Attempts to identify a spin–orbit coupling mechanism between the solar axial rotation and orbital revolution (e.g. Zaqarashvili, 1997; Juckett, 2000; Callebaut et al., 2012; Scafetta, 2012; Cionco & Soon, 2015), have been variously contested (e.g. Shirley, 2006; Holm, 2015), although the former acknowledged that a physical picture relating the Sun's rotation and revolution remains unclear. An implied connection between the Sun's equatorial rotation rate and the barycentric motion is postulated by Wilson et al. (2008b).

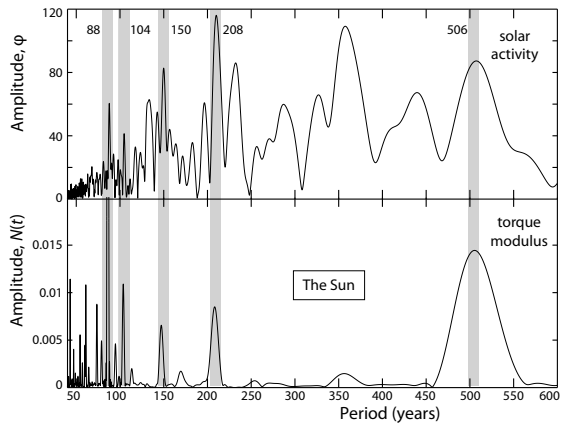


Figure 12.3: Comparison between solar activity and planetary torque. Top: Fourier spectrum of the solar activity quantified by the solar modulation potential  $\phi$ . Bottom: Fourier spectrum of the annual-averaged torque  $|N(t)|$ . The spectra display significant peaks with similar periodicities: the 88-yr (Gleissberg) and 208-yr (de Vries) cycles are the most prominent, but periodicities around 104 yr, 150 yr, and 506 yr are also seen. From Abreu et al. (2012, Figure 5), reproduced with permission © ESO.

Applying this speculative association to other systems, Perryman & Schulze-Hartung (2011) showed that behaviour advanced as being correlated with the Sun's activity, e.g. large changes in orbital angular momentum,  $dL/dt$ , and intervals of negative momentum, are common in exoplanet systems, and often significantly more extreme. HD 168443 and HD 74156 in particular, with  $dL/dt$  exceeding that of the Sun by  $>10^5$ , offer an independent opportunity to corroborate the hypothesised link between the Sun's barycentric motion and the many manifestations of solar activity. In particular, they offer independent tests of any theories of spin–orbit coupling.

### 12.1.7 Irradiance and other considerations

**Changes in irradiance** Long-term records of solar radiative output are central to an understanding of solar variability and past climate change. Although direct measures of solar irradiance are available only over the last 30 years, there is an extensive literature on interpretative methodologies and inferences (e.g. Ball et al., 2012; Li et al., 2012c; Fröhlich, 2013; Zacharias, 2014).

By attributing short-term variations of solar irradiance to changes in magnetic features on the solar surface, as implied by the past few decades (e.g. Ball et al., 2012), estimates of the evolution of the averaged magnetic flux can be computed from decadal values of cosmogenic isotope concentrations recorded in natural archives (including ice and vegetation), and employing a series of physics-based models connecting the processes from the modulation of the cosmic ray flux in the heliosphere to their record in natural archives (e.g. Vieira et al., 2011; Foukal et al., 2011; Krivova et al., 2011).

Over time scales of several hundred years, the Earth has experienced prolonged periods of mean temperatures both lower and higher than the present. Minima

include the pronounced *Maunder minimum* (as well as the Spörer and other minima), with the *medieval maximum* also well documented. The minima are correlated with periods of low sun spot numbers.

On Gyr time scales, the lower predicted luminosity of the young Sun, combined with the absence of evidence for widespread glaciation until  $\sim 2.3$  Ga, has led to the recognition of the ‘faint young Sun paradox’ (§12.3.8).

**Solar diameter and solar oblateness** Ground-based determinations of the solar diameter are limited by the atmosphere. Historical values from the transits of Mercury and Venus provide some constraints on the inferred solar luminosity in the past (e.g. Penna et al., 2010; Emilio et al., 2012; Sigismondi, 2013a,b).

The solar oblateness is driven by its (differential) rotation, interior composition, and atmosphere. Through  $J_2$ , it affects planetary perihelion precession (in the past it has been largely inferred from that of Mercury) and, in other stars, interpretation of exoplanet transits.

Measurements with SDO–HMI lead to an oblateness (Equation 6.68) of  $f = (R_{\text{eq}} - R_{\text{pol}})/R_{\text{eq}} = 8.34(\pm 0.15) \times 10^{-6}$  (Kuhn et al., 2012), significantly smaller than the value inferred from Mercury’s perihelion precession constrained by helioseismology, of  $f = 8.7 \times 10^{-6}$ . That the Sun is not as flattened as predicted has been described an ‘intriguing new conundrum in solar physics’ Gough (2012), perhaps attributable to unmodeled surface magnetic fields or turbulent stresses, and so emphasising the challenges in modeling stellar oblateness in high-accuracy exoplanet transit measurements.

Direct estimates of the (related) solar quadrupole moment,  $J_2$ , come from helioseismology, where values are  $\sim 2.2 \times 10^{-7}$  (Fienga et al., 2015, their Table 8), as well as from the latest solar system ephemerides, where estimates of  $1.80 \pm 0.25 \times 10^{-7}$  from INPOP10e (Fienga et al., 2013b) now yield  $2.20 \pm 0.12 \times 10^{-7}$  with the improved INPOP13c (Fienga et al., 2015, their Table 7).

**Mass loss** Although generally considered as constant, the Sun’s mass decreases at  $\sim 10^{-13} M_{\odot} \text{ yr}^{-1}$  carried by solar radiation (Krasinsky & Brumberg, 2004), with an uncertain increase due to (primarily cometary) matter falling onto it (Pitjeva & Pitjev, 2012). Secular acceleration in the mean longitudes of the inner planets currently places a limit of  $\dot{G}/G = -2 \pm 5 \times 10^{-14} \text{ yr}^{-1}$  (Pitjeva, 2005; Pitjeva & Pitjev, 2012), equivalent to the same limit on the determination of  $\dot{M}/M$  (Klioner, 2008).

Assuming  $\dot{G}/G = 0$ , solar system ephemerides constrain  $\dot{M}/M$  at similar accuracies, although experiments in INPOP13c are very sensitive to the asteroid mass included (Fienga et al., 2015, their Table 7).

**Solar radial velocity** Various studies have used the Sun as a template for radial velocity measurements, to serve as a more direct comparison with those of exoplanets (e.g. Meunier et al., 2010b; Pallé et al., 2013).

## 12.2 Planets

### 12.2.1 The terrestrial planets

Many aspects of the inner solar system planets and their satellites present constraints and challenges to models of planet formation and evolution. These include their detailed orbits, their internal structure and composition, and their surface geology, topography including impact cratering and, where appropriate, their atmosphere, hydrology, and magnetic fields. This section mentions just two specific topics which have (arguably) a particular relevance in the context of exoplanets.

**Mass of Mars** Time-dependent calculations of the structure and evolution of the primordial solar nebula during the viscous diffusion stage suggest that the value of the  $\alpha$  parameter of the protoplanetary disk (§10.3) was about 0.01 (Ruden & Lin, 1986). The assumption of a corresponding surface density distribution of the solar nebula which is smooth and monotonic, provides a reasonable match to the mass distribution in the solar system, which shows an overall radial trend from Uranus to Neptune approximated by  $r^{-3/2}$  (Weidenschilling, 1977b).

In comparison with this monotonic trend, the zones of Mercury, Mars and the asteroids, appear strongly depleted in mass (Weidenschilling, 1975, 1977b). Some aspect of planet formation, either its efficiency or the abundance of solids, appears to have prevented the growth of Earth-mass planets beyond 1 au.

**Possible origins** Processes which might take mass out of the Mars region were proposed by Safronov (1969) and Weidenschilling (1975), who suggested that planetesimals from the region of Jupiter would be perturbed into eccentric orbits, passing through the Mars/asteroid region, colliding and disrupting the planetesimals that had formed there.

In accretion models in which  $\alpha$  is a function of both radius and time, since  $T$  and  $\Sigma$  are functions of radius and time, Jin et al. (2008) found a sustained mass decrement in the surface density at the radius of Mars. They suggest that this leaves Mars gaining little mass during the final stages of chaotic growth, leaving it as a stranded embryo (Kleine et al., 2004a; Dauphas & Pourmand, 2011; Kobayashi & Dauphas, 2013).

In models invoking accretion in a protoplanetary disk truncated just past Earth’s orbit, the low mass of Mars and the depletion of solids in the asteroid belt are natural outcomes (Hansen, 2009; Raymond et al., 2009c; Walsh et al., 2011; Brasser, 2013; Izidoro et al., 2014a; Walsh & Levison, 2016; Haghighipour & Winter, 2016). Dynamical excitation and depletion, possibly through long-range interactions with Jupiter and Saturn, has also been invoked to explain the orbital architecture of the inner solar system (e.g. Wetherill, 1992; Raymond et al., 2009c; Izidoro et al., 2015c).

Two specific (and related) inner disk depletion/truncation mechanisms are detailed separately. In the presence of ‘sweeping secular resonances’, as the gas disk cleared, the inner region was partially cleared by the strong  $\nu_5$  resonance in the dissipating disk (§12.6.1). The gas giants may themselves have migrated through the disk, drifting inward to the terrestrial zone and then outward in a ‘Grand Tack’ that cleared material in their path (§12.6.4).

Table 12.2: Mass, radii (equatorial  $R_{\text{eq}}$ , polar  $R_{\text{pol}}$ , and mean  $\bar{R}$ ), mean density, gravity fields ( $J_2, J_4$ ), and rotation periods ( $P_\omega$ ) of the solar system giants, taken from the compilation of Guillot (2005, Table 1). Numbers in parentheses are the uncertainty in the final digits. Primary references are: (a) Campbell & Synnott (1985), (b) Campbell & Anderson (1989), (c) Anderson et al. (1987), (d) Tyler et al. (1989), (e) Lindal et al. (1981), (f) Lindal et al. (1985), (g) Lindal (1992), (h) from fourth-order figure theory (Zharkov & Trubitsyn, 1971), (i)  $(2R_{\text{eq}} + R_{\text{pol}})/3$ , (j) Davies et al. (1986), (k) Warwick et al. (1986), (l) Warwick et al. (1989). The Bond albedo,  $A_B$ , and effective temperature,  $T_{\text{eff}}$ , are determinations from Voyager–IRIS, as compiled by Guillot (2005, Table 2).

	Jupiter	Saturn	Uranus	Neptune
$M_p \times 10^{-26}$ [kg]	18.986 112(15) <sup>a</sup>	5.684 640(30) <sup>b</sup>	0.868 320 5(34) <sup>c</sup>	1.024 354 2(31) <sup>d</sup>
$R_{\text{eq}} \times 10^{-7}$ [m]	7.149 2(4) <sup>e</sup>	6.026 8(4) <sup>f</sup>	2.555 9(4) <sup>g</sup>	2.476 6(15) <sup>g</sup>
$R_{\text{pol}} \times 10^{-7}$ [m]	6.685 4(10) <sup>e</sup>	5.436 4(10) <sup>f</sup>	2.497 3(20) <sup>g</sup>	2.434 2(30) <sup>g</sup>
$\bar{R} \times 10^{-7}$ [m]	6.989 4(6) <sup>h</sup>	5.821 0(6) <sup>h</sup>	2.536 4(10) <sup>i</sup>	2.462 5(20) <sup>i</sup>
$\bar{\rho}$ [ $\text{Mg m}^{-3}$ ]	1.327 5(4)	0.688 0(2)	1.270 4(15)	1.637 7(40)
$J_2 \times 10^2$	1.469 7(1) <sup>a</sup>	1.633 2(10) <sup>b</sup>	0.351 60(32) <sup>c</sup>	0.353 9(10) <sup>d</sup>
$J_4 \times 10^4$	−5.84(5) <sup>a</sup>	−9.19(40) <sup>b</sup>	−0.354(41) <sup>c</sup>	−0.28(22) <sup>d</sup>
$P_\omega \times 10^{-4}$ [s]	3.572 97(41) <sup>j</sup>	3.835 77(47) <sup>j</sup>	6.206(4) <sup>k</sup>	5.800(20) <sup>l</sup>
$P_\omega$ [h]	9.92	10.65	17.24	16.11
$q$ (Equation 11.44)	0.089 23(5)	0.154 91(10)	0.029 51(5)	0.026 09(23)
Bond albedo, $A_B$	0.343(32)	0.342(30)	0.300(49)	0.290(67)
$T_{\text{eff}}$ [K]	124.4(3)	95.0(4)	59.1(3)	59.3(8)

**Water delivery to Mars** Estimates of the quantity of water on Mars suggest that it totals 6–27% of the Earth's present ocean, equivalent to 600–2700-m depth on its surface (Lunine et al., 2003). Broadly similar models to those proposed for water delivery to Earth (§12.3.4) suggest that smaller asteroids and comets from beyond 2.5 au provided its source (e.g. Izidoro et al., 2013; Tornabene et al., 2013). Such models are consistent with Martian geology (e.g. Breuer et al., 2016), the D/H value for Martian magmatic water derived from SNC meteorites, viz. some 1.2 – 1.6× Standard Mean Ocean Water, and the high D/H in present-day Martian atmospheric water interpreted in terms of H<sub>2</sub>O loss through atmospheric escape (Lammer et al., 2013a; Erkaev et al., 2014).

### 12.2.2 The solar system giants

There are four giant planets in the solar system: the *gas giants* Jupiter and Saturn, along with Uranus and Neptune which are also classified as gas giants, but whose less massive gas envelopes and distinct compositions also justifies their alternative designation as *ice giants*.

**Masses and radii** Detailed constraints on masses, radii, and internal structure are available (Table 12.2). Masses are derived from the motions of their natural satellites, radii are derived from radio occultations, and rotation periods are inferred from the time variation of their magnetic fields. All are relatively fast rotators, with periods of 10–11 h for Jupiter and Saturn, and 16–17 h for Uranus and Neptune (§12.4.5).

Estimates of  $J_2$  and  $J_4$ , and constraints on their interior density profiles, have been established from the Pioneer and Voyager spacecraft fly-bys. Figure 12.4 shows their inferred internal structures.

**Voyagers 1 and 2** Voyagers 1 and 2 were launched in 1977 and performed the ‘Grand Tour’ of the four outer planets. According to Evans (2008), in 1965, US aerospace engineer Gary Flandro noticed that the four planets would, in the mid-1970s, be aligned allowing a spacecraft to visit all four using a series of gravity-assists, with the alignment not occurring again for 176 yr. The necessary technology was developed just a few years before the planetary line-up allowed it. The preparatory Pioneer 10 and Pioneer 11 missions to Jupiter (and Saturn for Pioneer 11) were launched in 1972–73. In 2012 August Voyager 1 left the heliosphere and entered the interstellar medium.

**Jupiter and Saturn** Jupiter and Saturn consist mostly of H and He. Jupiter has  $R_J \sim 70\,000$  km ( $11R_\oplus$ ),  $M_J \sim 318M_\oplus$ , and an average density  $\rho_J = 1.33 \text{ Mg m}^{-3}$ , with elements heavier than He representing some 11 – 45 $M_\oplus$  of its total mass (e.g. Zharkov & Gudkova, 1991; Chabrier et al., 1992). Values for Saturn are  $R_S \sim 60\,000$  km ( $9.4R_\oplus$ ),  $M_S \sim 95M_\oplus$ , and  $\rho_S = 0.69 \text{ Mg m}^{-3}$ .

Structurally, they are believed to comprise small rocky cores at high temperature and pressure ( $\sim 30\,000$  K and  $\sim 3000$  GPa at the core boundary for Jupiter) but with poorly understood composition and properties. The surmised existence of cores is guided by plausible formation models, as well as by gravity measurements (which suggest a core mass of 12 – 45 $M_\oplus$  for Jupiter), although they may now be diluted, ill-defined, or even absent (Guillot et al., 1997; Guillot, 1999a; Guillot et al., 2004; Helled, 2011; Nettelmann, 2011; Nettelmann et al., 2012; Helled & Guillot, 2013; Miguel et al., 2016; Vazan et al., 2016; Helled & Stevenson, 2017).

Constraints on the core's location (and composition) at the time of formation come from models of the solar system formation. Generally assumed to have formed beyond the snow line, pebble accretion (§10.4.4) combined with migration might place this in the innermost part of the protoplanetary disk (Raymond et al., 2016).

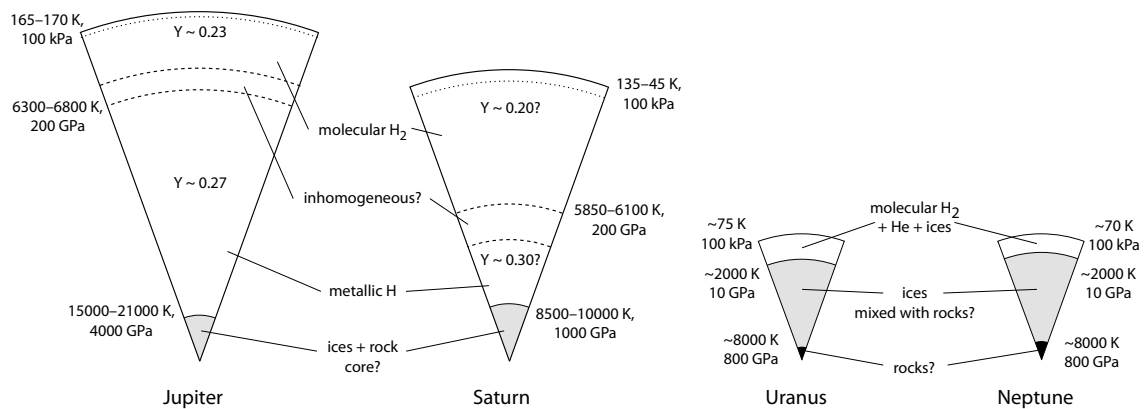


Figure 12.4: Schematic scaled representation of the interiors of the solar system giants. For Jupiter and Saturn, He mass mixing ratios  $Y$  are indicated. The size of their central rock and ice cores are very uncertain and, in the case of Saturn, the inhomogeneous region may extend down to the core. From Guillot (2005, Figures 6 and 9), by permission, Annual Reviews ©2005.

Surrounding the core is a thick dense layer of liquid *metallic hydrogen*, where extreme pressures result in unbound electrons, and the H is consequently electrically conductive and the source of the magnetic dynamo (Wigner & Huntington, 1935; Loubeyre et al., 1996; Weir et al., 1996; Chabrier et al., 1992; Saumon et al., 2000). Above is an electrically-insulating molecular outer layer comprising some 90% H and 10% He by volume, or some 75% H and 25% He by mass (close to the theoretical composition of the primordial solar nebula), with traces of  $\text{CH}_4$ ,  $\text{H}_2\text{O}$ ,  $\text{NH}_3$ , Si-based compounds, and others.

A detailed description of how models of the giant planet interiors are constructed is given by Militzer et al. (2016). The leading-order self-consistent, multi-layered, rotationally-distorted non-spheroidal model of Jupiter by Kong et al. (2016) produces the known mass, equatorial and polar radii, and quadrupole component  $J_2$  all within their error bars,  $J_4$  and  $J_6$  within 5%, along with a core equatorial radius  $0.09R_\oplus$  and a core density  $\rho_c = 20 \text{ Mg m}^{-3}$ , corresponding to  $3.73M_\oplus$ . Higher-order solutions yield the variation of the gravitational field due to zonal winds, with evidence for equatorially anti-symmetric zonal winds present in the odd zonal coefficients  $J_n$ ,  $n \geq 3$  (Kong et al., 2015).

**Juno mission** NASA's Juno mission, launched in 2011 August, entered Jupiter orbit in 2016 July (Bolton et al., 2017). It is measuring the composition, gravity and magnetic fields, and polar magnetosphere, targeting improved constraints on its moment of inertia and gravitational zonal harmonics. The precession rate of Jupiter's poles, and hence its moment of inertia, should be determined to  $\leq 0.1\%$  (Hubbard & Militzer, 2016; Le Maistre et al., 2016; Wahl et al., 2016; Kong et al., 2017).

Initial results, from precise Doppler tracking, show that Jupiter's gravity field is north-south asymmetric (signifying atmospheric and interior flows), with its non-zero odd harmonics ( $J_3, J_5, J_7, J_9$ ) demonstrating that the observed zonal cloud flow persists to depths of 3000 km below the cloud tops, and yielding

a mass of the dynamical atmosphere of  $\sim 0.01M_J$ . Its even harmonics ( $J_4, J_6, J_8, J_{10}$ ) show that the planet's deep interior rotates nearly as a rigid body, with differential rotation decreasing by at least an order of magnitude compared to the atmosphere (Guillot et al., 2018; Iess et al., 2018; Kaspi et al., 2018).

**Uranus and Neptune** Uranus ( $R_U \sim 25000 \text{ km} \sim 4R_\oplus$ ,  $M_U \sim 14.5M_\oplus$ ,  $\rho_U = 1.27 \text{ Mg m}^{-3}$ ) is believed to comprise a small rocky core of uncertain mass consisting of Fe, Ni and silicates ( $0.5 - 3.7M_\oplus$ ,  $\rho \sim 9 \text{ Mg m}^{-3}$ ,  $P \sim 800 \text{ GPa}$ ,  $T \sim 5000 \text{ K}$ ), an ice mantle of  $9.3 - 13.5M_\oplus$  composed primarily of  $\text{H}_2\text{O}$ ,  $\text{CH}_4$  and  $\text{NH}_3$ , and an outer gaseous H/He envelope of  $0.5 - 1.5M_\oplus$  extending from about 80–85% of its radius out to the cloud-tops. However, different rock/ice/gas compositions also satisfy the observations (Bergstralh et al., 1991; Lunine, 1993; Podolak et al., 1995; Helled et al., 2011; Podolak & Helled, 2012).

The 'ice mantle' is not composed of conventional ice, but is rather a hot dense fluid of high electrical conductivity.<sup>3</sup> This gradually merges into the outer gaseous atmosphere, with a 'surface' at about  $R \sim 25000 \text{ km}$  designated as the radius corresponding to an atmospheric pressure of 100 kPa (1 bar).

Neptune ( $R_N \sim 25000 \text{ km}$  or  $\sim 3.9R_\oplus$ ,  $M_N \sim 17.1M_\oplus$ ,  $\rho_N = 1.64 \text{ Mg m}^{-3}$ ) has an internal structure resembling but denser than that of Uranus, with a rocky core of  $\sim 1.2M_\oplus$ , an ice mantle of  $10 - 15M_\oplus$ , and an outer atmosphere of  $1 - 2M_\oplus$  (Lunine, 1993; Podolak et al., 1995; Podolak & Helled, 2012).

<sup>3</sup>The terms 'gas' and 'ice' are planetary-science designations for volatiles with exceptionally low melting points, or melting points above  $\sim 100 \text{ K}$ , respectively. The terms are applied irrespective of whether the compounds are solids, liquids or gases. In the case of the gas and ice giants, the majority of the 'gas' and 'ice' in their interiors is, in fact, hot and liquid.

**Formation** An outline of the formation of the solar system giants, in the framework of the core accretion model, is given in Section 10.5.1.

More recent numerical simulations of the formation of the giant planets and their cores, based on core-nucleated accretion models and with various assumptions on the surface densities of solid particles and grain opacities, suggest core formation times of order 1–5 Myr (e.g. Hubickyj et al., 2005; Lissauer et al., 2009; Movshovitz et al., 2010; Kobayashi et al., 2012). Radiative–convection cooling of self-consistent atmospheric models are given by Fortney et al. (2011b).

Their detailed physical properties do not in themselves imply an unambiguous mode of formation. Models for Uranus and Neptune face specific challenges (e.g. Jakubík et al., 2012; Ali-Dib et al., 2014b; Helled & Bodenheimer, 2014). Levison et al. (2001a) noted that, without other constraints, ‘the possibilities concerning the formation of Uranus and Neptune are almost endless’. In practice, numerous constraints, such as the Late Heavy Bombardment (box, page 669), the anomalously low mass of Mars (§12.2.1), and the chemical and phase-space distribution of various minor bodies in the solar system (§12.5), have allowed more quantitative models for their formation to be developed (§12.6).

These models are important because, while there are now hundreds of known giant exoplanets, only the most basic parameters of mass and/or radius can typically be measured. While the mean density is a powerful diagnostic, it is insufficient to give a detailed picture of the planetary interior. At present, only the planets in the solar system can be studied in sufficient detail to provide some sort of picture. The following details have been given by Helled et al. (2014).

**The gas giants Jupiter & Saturn** The basic components of any model are the conservation of mass and of momentum. The former is written as

$$\frac{dM}{dr} = 4\pi r^2 \rho(r) \quad (12.1)$$

where  $M(r)$  is the mass contained in a sphere of radius  $r$  and  $\rho(r)$  is the density at  $r$ . Conservation of momentum is given by

$$\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2} + \frac{2}{3}\omega^2 r \rho(r) \quad (12.2)$$

where  $P$  is the pressure, and  $\omega$  is the rotation rate. The second term is an average centrifugal term that allows for the effect of rotation. For Jupiter this amounts to a correction of ~2% in the interior, rising to ~5% near the surface. For Saturn it is about twice that. For Uranus and Neptune it is less than 1% except near the surface (Helled et al., 2014).

Temperature changes within the planet modify this simple framework, and depend on the mechanism of energy transport. Hubbard (1968) showed that in order to support the high thermal emission observed for Jupiter, most of its interior must be convective, and therefore this region can be well represented by an adiabat. It is generally assumed that the same is true for Saturn. The assumption of a strictly adiabatic temperature gradient is still quite standard, although Guillot et al. (1994b) have

suggested the possibility that Jupiter and Saturn might have radiative windows at temperatures of ~2000 K, while composition gradients can also modify the adiabatic gradient through double-diffusive convection (Leconte & Chabrier, 2012).

Even with the assumption of an adiabatic temperature gradient, the problem of computing the density profile is not straightforward. Equations of state have been measured experimentally for H, He, H<sub>2</sub>O, and some additional materials of interest, but there are still large uncertainties in the experiments and in their interpretation (e.g. Saumon et al., 1995; Nettelmann et al., 2008; Militzer et al., 2008). This leads to significant uncertainties in, for example, the estimated core mass of Jupiter and Saturn. The lack of knowledge on the depth of differential rotation in Jupiter and Saturn also introduces a major source of uncertainty to structure models.

Magnetic field effects in Jupiter and Saturn are expected to be small, and have mostly been ignored, but as measurements improve, including magnetic effects will become necessary. These will include pressure effects, as well as contributions to the viscosity that will affect the convective motions, and, as a result, the temperature gradient. These motions may also contribute to differential rotation in these planets, and may themselves be driven by differential rotation. In turn, magnetic field modeling may eventually provide useful limits on the location of conductive regions of the planet’s interior (e.g. Stanley & Bloxham, 2006; Redmer et al., 2011), and on the extent of the differential rotation.

A particular challenge for modeling is the choice of overall structure and composition. Traditional models of Jupiter and Saturn assumed a core of heavy material surrounded by a H–He envelope with some additional high-Z component (Podolak & Cameron, 1974; Saumon & Guillot, 2004; Soubiran & Militzer, 2016), but later models have also divided the envelope into a heavy element rich layer under a layer with more nearly solar composition (Chabrier et al., 1992; Guillot, 1999a; Nettelmann et al., 2012). The motivation for dividing the envelope is based on the idea that at high pressures not only does H change from the molecular to the metallic phase, but He may become immiscible in H and rain out to the deeper interior (Stevenson, 1975; Wilson & Militzer, 2010). The depletion of He in Saturn’s upper atmosphere has been observed (Gautier et al., 2006), and He rain has been advanced as an explanation for Saturn’s high thermal emission (Fortney & Nettelmann, 2010).

The assumption of a core was originally based on the need to match the low gravitational quadrupole moments of these planets (Demarcus, 1958). This assumption was later strengthened by the core accretion model, which requires a large heavy element core to initiate the capture of a H–He envelope. However, for both Jupiter and Saturn, interior models without cores can be found. Helled et al. (2014) provide more details of the uncertainties entering into the estimates of the core mass, including the equation of state for H, the uncertain envelope compositions, and the inability of the mass and moment of inertia to distinguish between a wide ranges of core densities (Podolak & Helled, 2012). Structural models are also being guided by detailed models of core growth and planetesimal accretion (Lozovsky et al., 2017, and references).

The internal density distribution of a planet cannot be measured directly, but some moments can be estimated. Because of the cylindrical hemispherical symmetry of a rotating planet, the moments are even functions of only the radius  $r$  and colatitude  $\theta$

$$J_{2\ell} = -\frac{1}{Ma^{2\ell}} \int r'^{2\ell} P_{2\ell}(\cos\theta') \rho(r', \theta') d^3 r' \quad (12.3)$$



where  $M$  is the mass,  $a$  is the average radius, and  $P_n$  is the  $n$ th-order Legendre polynomial. Interior models are constructed to fit the mass (essentially  $J_0$ ) and as many of the  $J_{2\ell}$  that can be measured. Each higher order  $J$  gives additional information on  $\rho(r)$ , although this information is more and more strongly weighted by high orders of  $r$ . In fact, only  $J_0$  (i.e., the mass) probes the core region, while higher  $J$  are only sensitive to the density distribution in the envelope. Since this is nearly independent of the core density, small changes in the envelope density caused by differences in the equation of state or in the assumed composition, can cause large changes in the estimated mass of the core, with the result that values between  $0 - 15M_{\oplus}$  have been suggested.

Results are also sensitive to the assumed composition of the envelope. For Jupiter, H and He account for  $\sim 90\%$  of the envelope by mass, while the high-Z component makes up the remainder. Thus the major contribution to  $\rho$  is due to H, and a small error in the equation of state of H may result in a much larger error in the estimated abundance of high-Z material (Podolak & Hubbard, 1998).

**The ice giants Uranus & Neptune** Giant planet formation models tend to concentrate on Jupiter-like planets. Lower-mass planets, such as Uranus and Neptune, are broadly considered to be ‘failed’ giant planets which, in the core accretion models, remain gas-poor due to their slow growth at larger distances for which runaway gas accretion cannot be established before the gas dissipates (e.g. Frelikh & Murray-Clay, 2017).

Modeling the interior structures of Uranus and Neptune is more difficult than for Jupiter and Saturn (Helled et al., 2014), in part because the high-Z component represents a much larger fraction of the total mass, but also because the thermal structure is not well known. Neptune has a strong internal heat source, so an adiabatic interior is a reasonable assumption, but Uranus is in equilibrium with solar insolation (e.g. Pearl & Conrath, 1991). In addition, thermal evolution models of Uranus give too long a cooling time for the planet (Fortney et al., 2011b). Some process like layered diffusion may be inhibiting heat flow in the planet, such that temperatures in the interior might be much higher than adiabatic.

Observational data for Uranus and Neptune also have much larger uncertainties. The gravitational moment  $J_2$ , flattening  $f$ , and angular velocity  $\omega$  are related to first order by

$$J_2 - \frac{2f}{3} + \frac{q}{3} \approx 0 \quad (12.4)$$

where  $q \equiv \omega^2 a^3 / GM$  is the ratio of centrifugal to gravitational forces. Rotation periods determined by the Voyager fly-bys, together with the measured values of  $J_2$  and  $f$ , do not satisfy this equation (Podolak & Helled, 2012), and Helled et al. (2010) has suggested that the rotation period of Uranus is significantly shorter, and that of Neptune significantly longer, than those determined by Voyager.

Uranus and Neptune have usually been treated using a three-shell models, comprising a core of rock, a shell of ‘ice’, and a H–He envelope in the solar ratio together with an admixture of high-Z material. More recent models have maintained the three-shell structure but have replaced the ice shell and envelope with an inner envelope containing H–He together with a large fraction of high-Z material and an outer envelope composed of H–He and a small mass fraction of high-Z material.

Beyond the assumption of a three-shell model, Helled et al. (2010) assumed that  $\rho(r)$  could be fit by a 6th-order polynomial, establishing an empirical equation of state that could be interpreted as requiring a continuous increase in the H–He mass

fraction with increasing radius. In addition, they have suggested that Uranus and Neptune could be rather ‘dry’, finding that the gravity data could be fit with silicates as well as water. This also raises the question whether Uranus and Neptune are truly icy planets, or alternatively, silicate-dominated planets, similar to Pluto (Simonelli & Reynolds, 1989).

Although Uranus and Neptune have similar masses and radii, they appear to be quite different internally. In addition to differences in heat flow, the radius of Uranus is larger than Neptune, but it is smaller in mass, with Neptune being more dense than Uranus by 30%. This difference is likely to be the result of differences in the formation history of these bodies. Giant impacts may have significantly affected their internal structure, leading to the observed dichotomy, and to prospects for determining their formation history from interior models (e.g. Stevenson, 1986; Podolak & Helled, 2012).

**Noble gas enrichment** The origin of the noble gas enrichment of Jupiter’s atmosphere, in particular Ar which condenses only at very low temperatures ( $\sim 30$  K), remains uncertain. Hypotheses include the delivery of planetesimals formed at very low temperatures (Owen et al., 1999); *clathration* (lattice trapping) of noble gases in ices (Gautier et al., 2001b; Hersant et al., 2004; Alibert et al., 2005c); or fractionation by photoevaporation due to far ultraviolet radiation from nearby massive stars (Monga & Desch, 2015).

The enrichment of C and possibly N in the atmospheres of Uranus and Neptune may similarly indicate impact of a significant planetesimal mass ( $\geq 0.1M_{\oplus}$ ) after the bulk of their H/He envelopes had been captured.

Noble gases in the lunar regolith are primarily delivered by the solar wind (Guillot, 2005). Species include apparently orphan radiogenic  $^{40}\text{Ar}$  and  $^{129}\text{Xe}$  in excess of the primordial solar origin, and therefore generally attributed to lunar degassing. In analogy with exoplanet host star pollution due to captured planets (§8.4.7), Ozima et al. (2004) considered that pollution of the Sun by a  $2M_{\oplus}$  capture could account for orphan Xe in the Moon.

**Jupiter: prerequisite for life?** That the Earth has been bombarded by asteroids and comets throughout its history is evidenced by its surface impact craters (e.g. Shoemaker, 1983; Chapman, 1994; Montanari et al., 1998; Morbidelli et al., 2001). The association was made at a time when most known objects in Earth-crossing orbits were long-period comets. Since a significant fraction of such comets is ejected from the solar system due to distant gravitational perturbations by Jupiter (Oort, 1950; Everhart, 1968; Wetherill, 1994), it was conjectured that without Jupiter, Earth would have been subject to an enhanced impact flux throughout its evolution (by a factor 10–100 according to Wetherill, 1994), which might have slowed or inhibited the development of life on Earth.

By analogy, it is often argued that a giant ‘sentinel’ planet, broadly with the orbit and mass of Jupiter, is a prerequisite for the development of life on a potentially habitable exoplanet (e.g. Ward & Brownlee 2000, pp. 238–239; Horner & Jones 2010).

**Effects of Jupiter on Earth impact rates:** Detailed dynamical integrations can be used to quantify the influence of the mass and orbit of a Jupiter-like sentinel on the Earth impact rate. Laakso et al. (2006) considered the escape rate of several thousand small cometary bodies due to Jupiter, and found that, in its current orbit, Jupiter may provide only minimal protection to the Earth.

Detailed studies according to the three distinct populations of potential Earth impactors have been made by Horner & Jones (2008), Horner & Jones (2009), and Horner et al. (2010) respectively. For near-Earth asteroids and short-period comets, their simulations followed the dynamical evolution of 100 000 massless test particles for 10 Myr under the gravitational influence of Earth, Mars, Jupiter, Saturn, Uranus and Neptune, and for 12 values of Jupiter's mass, ranging from  $0.01 - 2M_J$ , and for an inflated Earth radius of  $10^6$  km to accelerate collision rate estimates. As for Laakso et al. (2006), results for long-period comets were based on estimated escape rates.

They found that for the long-period comets (which represent only a minor contribution to the total impact flux at Earth), Jupiter indeed provides significant shielding, by ejecting such bodies from the solar system. For near-Earth asteroids and short-period comets, impact rates are markedly lower for planetary systems that include a massive Jupiter than for those that have a Saturn-mass (or slightly smaller) planet at the same location. However, for a sentinel planet mass  $\leq 0.15M_J$ , the Earth impact flux falls significantly, such that the impact rate without Jupiter would be even lower (Figure 12.5). They concluded that the notion that giant planets are required to ensure a benign impact regime for potentially habitable worlds to be truly habitable is not valid.

Extending the study to the sentinel planet's orbit, Horner & Jones (2012a) found that eccentricity is of secondary importance (compared to mass) in determining the impact flux. For objects from beyond the sentinel's orbit, its orbital inclination has little effect on the impact regime in the system's inner reaches, while increasing the sentinel's inclination has a significant effect on the dynamical stability of the asteroid belt, leading to  $> 50\%$  belt depletion on time scales of 10 Myr for all but the lowest mass sentinels, and suggesting that few objects would remain to pose a threat on astronomically significant time scales.

**Impactor populations** There are considered to be three main populations of potential Earth impactors, with different origins, and with Jupiter's role in their evolution varying accordingly:

(i) near-Earth asteroids (box, page 688), deflected into the inner solar system from the main asteroid belt, and possibly contributing the primary impact flux (e.g. Chapman, 1994; Morbidelli et al., 2002);

(ii) short-period, or Jupiter family, comets (Holman & Wisdom, 1993; Horner et al., 2004a; Horner & Lykawka, 2010a), with  $P \sim 5 - 6$  yr, and with aphelia in the vicinity of Jupiter's orbit. Their parent population are the Centaurs (e.g. Horner et al., 2003, 2004a,b), which in turn originate from the Edgeworth-Kuiper belt (Holman & Wisdom, 1993; Levison & Duncan, 1997), the scattered disk (Duncan & Levison, 1997), the inner Oort cloud (Emelyanenko et al., 2005), and the Jovian and Neptunian Trojans (Horner & Wyn Evans, 2006; Horner & Lykawka, 2010a,b). Short-period comets contribute a significant fraction of the Earth impact hazard and, depending on the frequency

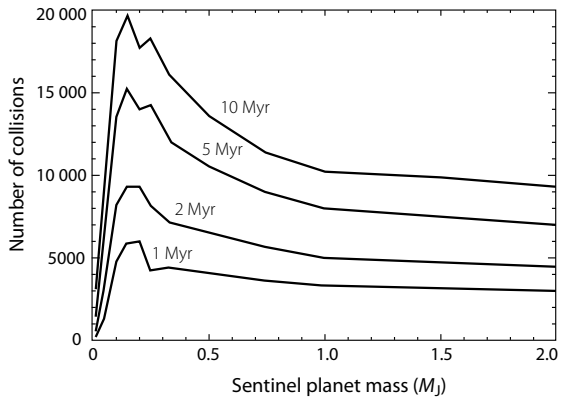


Figure 12.5: Collisions with an 'inflated' Earth ( $R_p = 10^6$  km) as a function of a Jupiter-like sentinel mass, at a sequence of times. The impact rate for a  $1M_J$  sentinel is  $3.5\times$  higher than for  $0.01M_J$ . The impact flux peaks between  $0.1 - 0.25M_J$ , due to the destabilising influence of the  $\nu_6$  secular resonance, which diverts objects from the inner asteroid belt into the near-Earth population. With lower sentinel mass, the resonance moves outward, disrupting a greater fraction of the belt, with maximum destabilisation between  $0.1 - 0.25M_J$ . From Horner & Jones (2008, Figure 3), reproduced with permission ©CUP.

with which they are deflected into the inner solar system (Steel et al., 1991), may represent the single largest component;

(iii) long-period comets (Oort, 1950; Kaib & Quinn, 2009), with  $P \sim 10^3 - 10^6$  yr, and probably representing the smallest contribution to the Earth impact flux. Their source is the Oort cloud, containing  $\sim 10^{13}$  cometary nuclei, typically  $\leq 10$  km in diameter, and occupying a thick shell surrounding the Sun at a distance of  $10^3 - 10^5$  au. Gravitational perturbations due to the Galactic tide, and to impulses by passing stars (§12.1.6), result in new long-period comets that may penetrate the inner solar system (Horner et al., 2003).

Taken in isolation, detailed models (box, page 662) suggest that a giant 'sentinel' planet is not necessarily a prerequisite for the presence of life. A more complete consideration of habitability would nevertheless have to take into account the impact flux required for the delivery of water from beyond the ice line, along with any positive effects of otherwise cataclysmic disruptions of a habitable planet's long-term evolution.

## 12.3 Earth–Moon system

### 12.3.1 Early chronology

The solar system was formed about 4.57 Gyr ago (§12.1.4) by the gravitational collapse of a protostellar cloud. Earth's early history has been inferred from a wide range of observations, and by appeal to planet formation models refined over the past decades.

During the first 500 Myr of the solar system's existence, Earth grew by colliding with other planetary embryos and planetesimals. The energies involved were sufficient to melt much of the growing planet, allowing dense Fe melts to sink to the centre to form Earth's core (e.g. Watters et al., 2009; Arkani-Hamed & Ghods, 2011).

**Earth's core, seismology, and polarity:** Henry Cavendish (1798) used gravitational attraction experiments to estimate that Earth's mean density is some 5.5 times that of water, leading to the idea that it could not be composed entirely of rock ( $\rho \sim 3-4$ ), and hence to the picture of a dense Ni–Fe core surrounded by a rocky mantle (Wiechert, 1898), the implied radial structure arising from planetary differentiation (§10.4.7). Inferred heating from its assumed gravitational collapse, supported by volcanic evidence, generally suggested that the Earth's interior was likely to be molten, although Lord Kelvin maintained that the presence of tides and the absence of rotational 'wobbling' precluded such a liquid core.

With the advent of (earthquake-driven) seismology, and from the fact that compressional primary or 'P' waves pass through it, while secondary elastic shear or 'S' waves do so only weakly, Oldham (1906) confirmed the existence of a liquid core, now known to be of radius  $\sim 3400$  km. Subsequently, Lehmann (1936) showed that there is, within this liquid core, a solid inner core of radius  $\sim 1220$  km (a little smaller than the Moon). Densities are between  $9.9\text{--}12.2\text{ Mg m}^{-3}$  in the outer core and  $12.6\text{--}13.0\text{ Mg m}^{-3}$  in the inner core. Based on the relative prevalence of various chemical elements in the solar system, the theory of planetary formation, and constraints from the chemistry of the rest of the Earth's volume, the inner core is believed to consist primarily of a Fe–Ni alloy, at  $T \sim 5700$  K and  $P \sim 330$  GPa. Such conditions can only be replicated in  $\mu\text{m}$ -sized quantities in the laboratory, via diamond compression, laser heating and X-ray probing (e.g. Anzellini et al., 2013).

The inner core, initially liquid, started to solidify at  $800\text{--}1000$  Ma (Labrosse et al., 2001). Gradual 'freezing' of the liquid outer core due to progressive cooling of the Earth's interior, at  $\sim 0.1\text{ K Myr}^{-1}$  (Jacobs, 1953), leads to the solid inner core increasing in radius by  $\sim 0.5\text{--}1.0\text{ mm yr}^{-1}$  (Waszek et al., 2011). Seismic propagation times N–S exceed those E–W by  $\sim 5$  s, constraining the form and orientation of its crystalline structure (Cottenier et al., 2011), and its relation to the overall magnetic field. Further substructure and anisotropies exist within the solid inner core itself (e.g. Poupinet et al., 1983; Wang et al., 2015g).

That a compass needle points north had been known since the twelfth century, and ascribed to the existence of a 'magnetic island' in the northern hemisphere, or to the pole star or 'lodestar' (Polaris). William Gilbert (*De Magnete*, 1600) instead concluded that the Earth itself is the source of the magnetic field. Bullard & Gellman (1954) inferred that the field is generated by dynamo action in the outer liquid core, in which Coriolis- and convective-driven turbulent motion of the molten iron generates electric currents and, in turn, magnetic fields. The geomagnetic field orientation changes with time: magnetic north is currently moving at about  $60\text{ km yr}^{-1}$ , although shifts of up to  $6^\circ$  per day have occurred (Coe et al., 1995).

From paleomagnetic evidence in the geological record, the geomagnetic field is known to reverse polarity at irregular intervals of some  $200\,000\text{--}300\,000$  yr. Such periods are termed *chrons*, while brief disruptions that do not result in reversal are called *geomagnetic excursions*. Typical reversals take some  $1000\text{--}10\,000$  yr, although the most recent (Brunhes–Matuyama) reversal,  $780\,000$  years ago, may have occurred within a human lifetime (Sagnotti et al., 2014). A brief complete reversal (the Laschamp event) occurred  $41\,000$  yr ago during the last glacial period, lasting (only) about  $440$  yr, with the change of polarity lasting around  $250$  yr, and with the magnetic field weakening to 5% of its present strength (e.g. Nowaczyk et al., 2012). The geomagnetic field may disappear entirely during reversals (McCormac & Evans, 1969).

Reversals may be due to instabilities as in the Sun, which undergoes spontaneous reversals every  $9\text{--}12$  yr. Other proposed mechanisms include triggering by external impact events (Muller & Morris, 1986), or as a result of continental slabs carried down into the mantle by plate tectonics at subduction zones (McFadden & Merrill, 1986). Models based on fluid dynamics and magnetic fields (e.g. Nakamichi et al., 2012) are unable to predict the future behaviour of the geomagnetic field.

Reversals will be accompanied by diminished protection afforded by the geomagnetic field from cosmic rays and the solar wind, with associated effects on the biosphere. Hypotheses have been advanced linking reversals to mass extinctions (Raup, 1985). The ends of 'superchrons' may have resulted in vigorous convection leading to widespread volcanism, with the subsequent airborne ash causing extinctions (Courtillot & Olson, 2007). Statistical analysis, however, shows no compelling evidence for a correlation between reversals and extinctions (Plotnick, 1980; Glassmeier & Vogt, 2010).

The young Earth would have been subject to substantial collisions with other protoplanets that may have re-melted the entire planet several times, leading to prolonged core formation, atmospheric outgassing, and deepening of the magma ocean as the Earth grew (Carlson et al., 2014). The accretionary phase culminated in the collision of the proto-Earth with a giant impactor, less than  $100$  Myr after the birth of the solar system, with ejected material coalescing to form the Moon (§12.3.3).

The subsequent decline of giant impact events, and the progressive cooling of the Earth's surface, would have allowed the formation of an initial planetary crust. Later tectonic processes destroyed all remnants of both the initial crust and the meteoritic impact sites on Earth. Final traces of this 'terminal bombardment' are evidenced by the cratering of the lunar and other surfaces (box, page 669).

Energy released during the final bombardment may have sustained widespread hydrothermal activity within Earth's crust, and may have proved conducive to life's emergence and early diversification. Core formation also depleted the bulk silicate Earth of siderophile elements (§10.4.7). According to this model, Earth's mantle and crust should be largely devoid of highly-siderophile elements, apart from epithermal-type deposits. An inferred terminal bombardment replenished some of the mantle's precious metal content during the 'Late Veneer' epoch more than  $3.9$  Gyr ago (box, page 669).

### 12.3.2 Earth's core

During Earth's early collisional growth phase, the release of substantial potential energy through sinking, together with internal heating through the decay of short-lived radioactive elements, resulted in the turbulently-spinning super-heated liquid core which maintains the

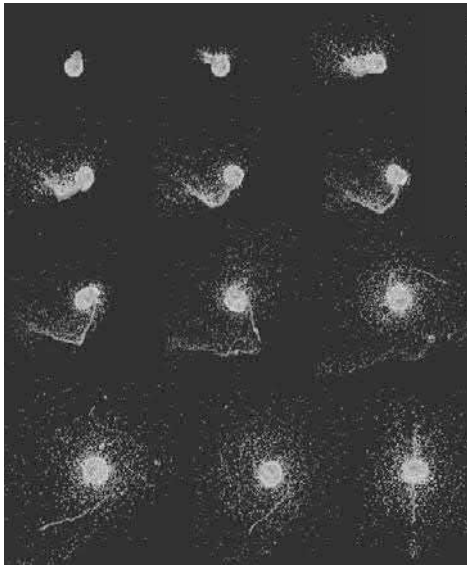


Figure 12.6: Hydrodynamic simulations of the Moon's formation as a result of an oblique giant impact between the Earth and a  $6 \times 10^{23}$  kg protoplanet. Results are projected onto the impact plane at times  $t = 0.3, 0.7, 1.4, 1.9, 3, 3.9, 5, 7.1, 11.6, 17$  and  $23$  h after impact (left to right); the final frame is  $t = 23$  h viewed edge-on. From Canup & Asphaug (2001, Figure 1), courtesy of Robin Canup, Southwest Research Institute.

magnetic field shielding Earth from the solar wind. Considerable diagnostic information is now available on the Earth's internal structure, its inner core, and this associated magnetic field (box, page 663).

### 12.3.3 The Moon

**Origin** It was originally hypothesised that the Moon had formed by centrifugal spin-off from the Earth (Darwin, 1879b, 1898; Binder, 1974). Subsequent models included gravitational capture (Gerstenkorn, 1955), and co-accretion of the Earth and Moon (Shmidt, 1958).

The current paradigm is that the Moon formed from the debris of a slow, grazing impact of a giant planetesimal, designated *Theia* (e.g. Daly, 1946; Hartmann & Davis, 1975; Cameron & Ward, 1976; Benz et al., 1989; Cameron & Benz, 1991; Baldwin & Wilhelms, 1992; Canup & Righter, 2000; Asphaug, 2014; Barr, 2016). A historical perspective is given by Hartmann (2014).

Hydrodynamic simulations suggest an oblique late-stage collision between Earth and a  $6 \times 10^{23}$  kg ( $\sim M_{\text{Mars}}$ ) protoplanet (Canup et al., 1999; Canup & Asphaug, 2001; Canup, 2004a,b; Belbruno & Gott, 2005; Halliday, 2008; Canup, 2012; Herwartz et al., 2014). Similar mass estimates have been derived from models of the giant impact phase of terrestrial planet formation (Jacobson & Morbidelli, 2014, see also §12.6.4).

Simulations by Canup & Asphaug (2001) show that the impacting cores rapidly coalesce (Figure 12.6), while

the liquid and vapour disk solidifies and accretes into a single satellite in  $\sim 1000$  yr (Kokubo et al., 2000; Pahlevan & Stevenson, 2007; Ward, 2012). Lunar samples indicating a once-molten surface support an impact origin.

Detailed models must address the Earth's apparently non-chondritic composition, and the similarity of their isotope ratios (notably  $^{182}\text{W}$ , whereas a giant impact is expected to generate a significant excess in the Moon), questions which have been rather well if not entirely resolved (e.g. Halliday, 2000; Asphaug, 2014; Bonsor et al., 2015; Mastrobuono-Battisti et al., 2015; Meier et al., 2014; Wohlers & Wood, 2015; Akram & Schönbächler, 2016; Hosono et al., 2017; Kruijer & Kleine, 2017; Mastrobuono-Battisti & Perets, 2017). They must also satisfy dynamical probabilities (e.g. Ringwood, 1989; Belbruno & Gott, 2005; Rufu et al., 2017). In the canonical scenario, the Moon forms predominantly from impactor material, contradicting the Moon's close geochemical similarity to Earth (e.g. Herwartz et al., 2014). For these reasons, alternative impact scenarios remain under consideration:

- (a) larger impact masses can produce a disk with the same composition as Earth's mantle, consistent with Earth–Moon compositional similarities (Canup, 2012). Such impacts would require subsequent removal of angular momentum from the Earth–Moon system, either through an *evection resonance* (§10.8.3) with the Sun (Čuk & Stewart, 2012; Ward & Canup, 2013), or via the related dynamical phenomenon of a phase-space trajectory *limit cycle* (Wisdom & Tian, 2015; Tian et al., 2017b);
- (b) debris disk collapse following a succession of smaller body impacts ( $0.01 - 0.1 M_{\oplus}$ ), perhaps more likely dynamically, and resulting in more similar geochemical signatures between Earth and Moon, has been suggested both qualitatively (Ringwood, 1989) and more quantitatively (Rufu et al., 2017). Other post-giant impact processes might have led to the similar  $^{182}\text{W}$  compositions of the pre-Late Veneer Earth's mantle and the Moon (Kruijer & Kleine, 2017);
- (c) 'hit-and-run' type collisions, with higher impact velocity and steeper impact angle, yield hotter debris disks with a larger fraction of target body material, easing isotope disparity (Asphaug, 2010; Reufer et al., 2012; Čuk et al., 2016b).

More generally, a giant impact phase is a recurrent feature of the 'post-oligarchic phase' of planet formation, and Mercury's high density may indicate that it lost much of its mantle during one or more impacts with another embryo (§10.4.5).

**Impact epoch** Various observations constrain the epoch of the Moon-forming impact. Low Fe in the lunar mantle suggests that the impact occurred subsequent to Earth's accumulation and differentiation (Tonks & Melosh, 1992). From a correlation between the timing of

the last giant impact and the mass that the planet subsequently acquires, the *late-accretion mass* (box, page 669), Jacobson & Morbidelli (2014) give  $t > 65 - 120$  Myr after solar system formation for a late-accretion mass  $4.86 \times 10^{-3} M_{\oplus}$ , and  $t > 50$  Myr for  $0.01 M_{\oplus}$ .

Various estimates derive from geochronology (box, page 653). The absence of a clear  $^{182}\text{W}$  excess in lunar samples implies  $t > 50$  Myr (Touboul et al., 2007). Similar geochronology epochs are inferred from Pb–Pb (Alègre et al., 2008) and Rb–Sr (Halliday, 2008), but with discordant results from Hf–W (Yin et al., 2002) and Lu–Hf (Taylor et al., 2009). Further constraints come from the large-scale lunar topography (Garrick-Bethell et al., 2014), and from detailed impact models and heating signatures (Bottke et al., 2015), with a reasonable consensus placing the impact at about 4.47 Ga.

A quantitative model for the early lunar atmosphere, including the radiative environment of the early Sun and post-impact Earth and a cooling global magma ocean, is given by Saxena et al. (2017).

**Structure and orbit** The Moon's internal structure is constrained by its mass, moment of inertia, and  $k_2$  and  $h_2$  tidal Love numbers (e.g. Matsuyama et al., 2016). Experimental constraints include Apollo seismic data, lunar laser ranging from Earth using the five retroreflector arrays placed by Apollo 11, 14, and 15, and Lunokhod (Dickey et al., 1994), and with orbiting missions notably the Lunar Reconnaissance Orbiter with its Lunar Orbiter Laser Altimeter (LOLA), and from gravity field measurements, most notably from GRAIL.<sup>4</sup>

The Moon's orbit and rotation is described by the JPL DE430 and DE431 ephemerides (§12.4.1), in part based on lunar laser ranging from different observatories on Earth since 1970 (Folkner et al., 2014; Kudryavtsev, 2016). Most recent data, including GRAIL, indicate a fluid core, a tidal acceleration in mean longitude of  $-25.90$  arcsec  $\text{cy}^{-2}$ ,  $\Delta a = +38.2$  mm  $\text{yr}^{-1}$  and  $\Delta e = +1.48 \times 10^{-11}$   $\text{yr}^{-1}$  (Pavlov et al., 2016).

**Tidal rhythmites** Celestial mechanics describes the changing lunar orbit due to tidal dissipation (e.g. Goldreich, 1966b; Chen & Nimmo, 2016), but direct constraints are also available from Earth's geological record (e.g. Sonett et al., 1996; Williams, 2000; Coughenour et al., 2009; de Azarevich & Azarevich, 2017).

Paleotidal and paleorotational values from Neoproterozoic (late Precambrian) tidal sedimentary *rhythmites* indicate that,

<sup>4</sup> NASA's GRAIL (Gravity Recovery and Interior Laboratory) mission, operational in lunar orbit between 2011–2012, performed gravity field mapping based on the  $1 \mu\text{m}$  precision separation measurements between two spacecraft, GRAIL A (Ebb) and GRAIL B (Flow). Objectives included mapping the structure of the lunar crust and lithosphere, determining the subsurface structure of impact basins and *mascons* (gravity anomaly mass concentrations, Melosh et al., 2013), and constraining its interior structure including the size of the inner core (Andrews-Hanna et al., 2013; Wieczorek et al., 2013; Zuber et al., 2013a,b; Matsumoto et al., 2015a; Pavlov et al., 2016).

around 620 Ma, there were  $13.1 \pm 0.1$  synodic lunar months  $\text{yr}^{-1}$ ,  $400 \pm 7$  solar days  $\text{yr}^{-1}$ , a day length of  $21.9 \pm 0.4$  h, and a relative Earth–Moon separation  $a/a_0 = 0.965 \pm 0.005$  (Williams, 2000). The resulting mean lunar recession rate since is  $21.7 \pm 3.1$  mm  $\text{yr}^{-1}$ , compared with  $38.2 \pm 0.7$  mm  $\text{yr}^{-1}$  today.

Three intervals show particularly high rates, almost twice that of today (de Azarevich & Azarevich, 2017): the Archean–Paleoproterozoic ( $69.3$  mm  $\text{yr}^{-1}$ ), Neoproterozoic–Ediacaran ( $70.1$  mm  $\text{yr}^{-1}$ ) and Ediacaran–Cambrian ( $64.8$  mm  $\text{yr}^{-1}$ ). Each coincides with enhanced meteoritic Earth or Moon impacts, and a reconfiguration of land mass that generated changes in the Earth rotation (and enhanced lunar recession), as well as processes of glaciation/deglaciation.

Earlier Precambrian rhythmites may permit the lunar orbit to be traced nearer to the time of its origin (Williams, 2000).

**Orbit and figure** A long-standing issue with the giant impact model of the Moon's origin is its  $5^\circ$  inclination to the ecliptic, referred to as the *lunar inclination problem*. Starting from a near-equatorial orbit, forward integration predicts a modern inclination at least an order of magnitude smaller than the observed value (Goldreich, 1966b; Ćuk et al., 2016b). Suggested explanations have included an (unlikely) second large Earth impact (Canup, 2004a), or various solar (Touma & Wisdom, 1998) or disk-type (Ward & Canup, 2000) resonances.

Pahlevan & Morbidelli (2015) argue that the present lunar orbit provides a sensitive record of gravitational interactions with Earth-crossing planetesimals that were not yet accreted at the time of the Moon-forming event. The lunar orbit can be reproduced by invoking interaction with a small quantity of mass, carried by a few bodies (and corresponding to  $\sim 0.01 M_{\oplus}$  eventually accreted on Earth), consistent with the constraints and models of a 'late accretion' (box, p 669). Although the model has a stochastic element, they found that the observed value of the lunar inclination is among the most likely outcomes for a wide range of parameters.

Anderson & Nieto (2010) reported an anomalous secular increase of the Moon's orbital eccentricity, as determined by lunar laser ranging, of  $\dot{e} = (9 \pm 3) \times 10^{-12}$   $\text{yr}^{-1}$ . Various explanations have been put forward (e.g. Iorio, 2011c; Williams & Boggs, 2016).

A distinct problem, noted by Laplace, has been to reconcile the observed lunar figure (with its larger than expected rotational and tidal bulges) with its present orbital and rotational state. Keane & Matsuyama (2014) found it could be resolved by properly accounting for lunar impact basins and mascons (footnote, page 665).

**Synchronous rotation** The Moon is synchronously rotating in the 1:1 spin–orbit resonance state with low eccentricity ( $e = 0.0549$ ), a nearly perfect equilibrium state characteristic of the end-point of dynamical spin–orbit evolution (Hut, 1980). In the giant impact theory of the Moon's origin, tidal dissipation is responsible for the expansion of the orbit and eccentricity damping (Ćuk & Stewart, 2012). Capture into the 1:1 spin–orbit resonance is not, however, the only outcome.

**Water on the Moon:** Liquid water cannot persist at the Moon's surface due to the decomposition of H<sub>2</sub>O vapour by sunlight. The Moon's small axial tilt, and the insulation properties of the lunar regolith, nonetheless led to the conjecture that H<sub>2</sub>O-ice may persist in the permanently-shadowed polar craters (Watson et al., 1961; Arnold, 1979). Water, and the hydroxyl group (–OH), may also exist as hydrates and hydroxides (Lodders & Fegley, 1998).

A Theia-type origin would have strongly depleted pre-existing volatiles, although a hot gas envelope may have offered some protection. Part of the interior may even have escaped widespread melting and degassing and simply inherited H<sub>2</sub>O from the proto-Earth (Saal et al., 2013), a hypothesis which has circumstantial support from the GRAIL gravity anomalies (Andrews-Hanna et al., 2013). Water may have been subsequently delivered through bombardment by minor solar system H<sub>2</sub>O-bearing bodies, continuously produced *in situ* by the impact of solar protons on oxygen-bearing minerals, or from magmatic degassing during lunar volcanic eruptions (Saal et al., 2013).

Evidence for the existence of water on the Moon has a lengthy history. In the early 1970s, trace quantities were found in rock samples returned by Apollo, but attributed to contamination. Water was detected in regolith returned to Earth by Luna 24 (Akhmanova et al., 1978). Clementine radar results suggested H<sub>2</sub>O-ice at the south pole, later disputed (Campbell et al., 2006; Zuber et al., 2012). Other inconclusive evidence, and non-detections, came from the Lunar Prospector in 1998, the Cassini–Huygens fly-by in 1999, Deep Impact spectroscopy in 2005, the Kaguya probe in 2007, and Chang'e 1 in 2007.

Detections were made from the Chandrayaan–1 Moon Impact Probe (MIP, Sridharan et al., 2010), and by its Moon Mineralogy Mapper (M<sup>3</sup>, Pieters et al., 2009), suggesting H over large parts of its surface. Further evidence came from NASA's Lunar Reconnaissance Orbiter–LCROSS (Colaprete et al., 2010; Neish et al., 2011).

Melt inclusions in the Apollo 17 sample 74220 reach ~1000 ppm (Hauri et al., 2011). Saal et al. (2013) found similar D/H isotope ratios in lunar volcanic glass and olivine-hosted inclusions from Apollo 15/17, demonstrating that lunar magmatic water has a composition indistinguishable from bulk H<sub>2</sub>O in carbonaceous chondrites, and similar to terrestrial H<sub>2</sub>O, implying a common origin for water in the interiors of the Earth and Moon (Boyce et al., 2014).

In summary, the Moon may have H<sub>2</sub>O locked in minerals, scattered in the regolith, and possibly ice at depth.

Realistic models of tidal dissipation combine viscoelasticity with inelastic creep (Efroimsky & Lainey, 2007; Efroimsky & Williams, 2009; Efroimsky, 2012a; Efroimsky & Makarov, 2013). In the formulation of Efroimsky (2012a), the secular tidal torque is described by a Darwin–Kaula expansion. Each term assumes, in the vicinity of the appropriate resonance, a kink-like shape, swiftly but continuously changing sign, vanishing at the resonance frequency, and efficiently trapping the spin rate into higher-order spin–orbit resonances.

Such a model predicts that the Moon could have been captured into the current 3:2 spin–orbit resonance with a probability as high as 0.6, but strongly dependent

on the temperature and mean viscosity of the Moon's interior; a warmer less-viscous Moon, and with larger  $e$ , would have been even more easily captured into such a higher resonance (Makarov, 2012, 2013).

Makarov (2013) suggests two paths leading to the actual 1:1 spin state. A cold Moon (less yielding to tidal forces), on a low- $e$  orbit, would naturally traverse the higher-order resonances before reaching the 1:1 spin–orbit state. Alternatively, the Moon could have formed with a retrograde rotation. Earth tides would then slow down the retrograde spin, traversing the weaker 1:2 resonance on its way to the 1:1 resonance.

**Effect on Earth's obliquity** Earth's obliquity (axial tilt) is ~23°, with a 40 000 yr-oscillation period, and 1.3° amplitude, stabilised over long periods by the Moon. In ~1.5 Gyr, as the Moon recedes from Earth, the obliquity will enter a chaotic period, varying in the range 0 – 85°.

Without it, Earth's obliquity would be chaotic, although the range over which it varies over a given interval depends sensitively on the resonances that drive the chaotic motion (Laskar et al., 1993). Their frequency map analysis showed that the obliquity could vary between 0 – 85°, a result *'leaving an impression in the astrobology community that a big moon is necessary to maintain a habitable climate on an Earth-like planet'* (Lissauer et al., 2012a). However, estimates of the resulting characteristic Lyapunov coefficient (§10.9.4), as well as the chaotic diffusion rate, suggest that stochastic changes in Earth's obliquity would be sufficiently slow so as not to preclude long-term habitability (Atobe et al., 2004; Lissauer et al., 2012a; Li & Batygin, 2014b).

Specifically, in Moon-less simulations with various initial conditions, Lissauer et al. (2012a) found that while the obliquity would vary much more than the actual Earth over 10<sup>5</sup> yr intervals, it remains within 20 – 25° for hundreds of Myr. None show obliquities spanning more than 65% of the range allowed by frequency-map analysis. They conclude that a large moon is not needed to stabilise an 'Earth' on time scales relevant to the development of advanced life.

**Biospheric relevance** Aside from the issues of obliquity variations, the Moon may have assisted life on Earth in other ways (e.g. Jheeta, 2013): (1) the impact which created the Earth–Moon system would have removed any primordial atmosphere, reducing the risk of an atmosphere hostile to life; (2) impact heating might have played a role in the generation of Earth's unusually strong magnetic field, which shields it from the solar wind; (3) the larger tides raised by the Moon would have enhanced wet/dry cycles in tidal pools, perhaps crucial for encouraging polymerisation as a precursor for life.

**Total eclipse** The near equality in angular size of the Sun and Moon as subtended on Earth, and the consequent phenomenon of the total solar eclipse, is generally regarded as coincidence. Balbus (2014) has noted that it is a consequence of their comparable tidal forces, itself implying strong temporal modulation, particularly pronounced during the Devonian

period (~400 Ma) when the first tetrapods appeared on land. Since even a modest difference in relative angular size would lead to a qualitatively different tidal modulation, Balbus (2014) has suggested that their similarity may not be entirely coincidental, and may have an anthropic basis.

**Application to exoplanets** The common occurrence of slow oblique impacts in simulations of post-oligarchic stages of terrestrial planet formation suggests that planets like Earth and Venus may experience at least one such impact during formation, and that large, impact-generated satellites may, accordingly, be common (Agnor et al., 1999; Barr & Bruck Syal, 2017).

Studies of the evolution of the impact debris of such a Moon-forming impact suggest that condensates deplete rapidly on 1000-yr time scales, while boulders (of uncertain size distribution) would deplete dynamically accompanied by collisionally-generated dust (Jackson & Wyatt, 2012). The inferred luminosity suggests that a Moon-forming event would be detectable in the Spitzer 24  $\mu\text{m}$  surveys for some 25 Myr after impact, with short-lived optically-thick emission spikes arising from the vapour condensates. Candidates for such events are described further in Section 10.6.4.

Jackson & Wyatt (2012) inferred that the number of 10–100 Myr stars with warm dust implies that the fraction that form terrestrial planets is  $\lesssim 10\%$ . For this to be higher would require either that terrestrial planets are largely fully-formed when the protoplanetary disk disperses, or that impact-generated debris consists purely of sub-km objects such that its signature is short-lived.

### 12.3.4 The origin of water on Earth

The location of the snow line at  $\sim 3$  au in the solar nebula (§11.2.3) suggests that water in the early solar system was largely restricted to its outer regions, beyond the asteroid belt. A key problem in planetary science is to identify the origin of  $\text{H}_2\text{O}$  on Earth, and to explain its abundances elsewhere in the inner solar system.

Elsewhere in the inner solar system, Mars Odyssey (GRS) has evidenced ice under a thin dust layer above  $60^\circ$  latitude in both hemispheres (Boynton et al., 2002). The deuterium/hydrogen (D/H) ratio of Venus is  $\sim 100$  times that of Earth's oceans, and is explained by  $\text{H}_2\text{O}$  loss through ultraviolet photodissociation high in the Venusian atmosphere (Donahue & Pollack, 1983). Mercury and the Moon appear superficially dry (box, page 666), possibly due to volatile loss in giant impacts.

Of the various origins considered for the  $\text{H}_2\text{O}$  on Earth, *endogenous sources* include water adsorbed by dry silicate grains in the solar nebula (Stimpfl et al., 2004; Drake et al., 2004), or through later-stage oxidation of a H-rich atmosphere (Ikoma & Genda, 2006).

Proposed *exogenous sources* include water delivery to Earth through impacts of comets, asteroids, and planetesimals (e.g. Chyba, 1990; Morbidelli et al., 2000; Lu-

nine et al., 2003; O'Brien et al., 2006; Drake & Campins, 2006; Raymond et al., 2004, 2006c, 2007a, 2009c).

Challenges in constructing a consistent model include accounting for (a) observational constraints on the total mass of water; (b) isotopic differences between water found in the Earth's oceans and that associated with the potential water carriers; (c) dynamical models of the perturbation of the outer solar system bodies into Earth-crossing orbits, also taking account of the epoch at which the bulk of Earth's water was delivered; and (d) dynamical models of the impact events, and whether they lead to some form of coalescence (and hence water delivery), or fragmentation (and hence water loss).

Further complications include  $\text{H}_2\text{O}$  adsorption as a function of the disk temperature profile (e.g. Boss, 1996b; Muralidharan et al., 2008; Albarède, 2009); the non-monotonic evolution of the snow line during the early phases of the solar system, with consequences for the relative hydration and isotopic differences for Venus, Earth and Mars (Garau & Lin, 2007); and the recent discovery of 'main belt comets' (§12.5.7).

Evolutionary models including a dynamical rearrangement of its outer bodies, specifically the 'Nice model' (§12.6.3), and the 'Grand Tack model' (§12.6.4), further complicate the picture, but appear to support the current model of water delivery.

**Earth's water composition** Compared with the outer comets comprising some 80% ice (e.g. Jessberger et al., 1989), or even carbonaceous chondrites carrying up to 10% water (Morbidelli et al., 2000), Earth contains only a small fraction of water, although still substantially more than expected in a body formed at 1 au from the Sun.

Some 0.02% of Earth's mass is in its surface oceans ( $O_\oplus \sim 1.4 \times 10^{21}$  kg). The amount in the mantle is some  $10 O_\oplus$  (Drake & Campins, 2006; Pearson et al., 2014a), with that in the interior estimated as  $1 - 50 O_\oplus$ , with  $4 - 12 O_\oplus$  (1000–3000 ppm) inferred via radiogenic Ar (Marty, 2012). Knowledge of the concentration, distribution, and delivery of  $\text{H}_2\text{O}$  to Earth, and its effects on phenomena such as differentiation, seismic properties, plate tectonics, and volcanism is reviewed by Peslier et al. (2017). Current understanding of the nature and distribution of  $\text{H}_2\text{O}$  and  $\text{H}_2\text{O}$ -rich materials from the water snow line to the Kuiper Belt is reviewed by Grasset et al. (2017).

The isotopic composition of W. Australian zircons indicates that there was already  $\text{H}_2\text{O}$  on the Earth's surface, and therefore a hydrosphere interacting with the crust, around 4.3–4.4 Ga (Wilde et al., 2001; Mojzsis et al., 2001; Nemchin et al., 2006; Ushikubo et al., 2008).

**Isotopic constraints** The compositional gradient of planetesimals and planetary embryos in the solar nebula, in particular of their volatiles, depends on their thermal evolution during their growth, itself determined by local solar heating, concentration of radioactive nuclides, proximity to the solar magnetic field, and their final size (Nuth, 2008; Cleeves et al., 2014).

Although comets were originally considered as an attractive exogenous water source (and delivery to Jupiter's stratosphere from the comet Shoemaker–Levy 9 impact of 1994 has been inferred from Herschel; Cavalié et al. 2013), there are isotopic and dynamical constraints that a detailed model must

satisfy. The D/H ratio of water in eight Oort cloud comets are on average twice that of (Vienna) Standard Mean Ocean Water (SMOW<sup>5</sup>), and fifteen times the D/H ratio of the early solar nebula (Hartogh et al., 2011, Figure 2). While comets formed in the warmer regions of Jupiter's orbit have lower D/H (Owen & Bar-Nun, 1995; Delsemme, 1998; Albertsson et al., 2014), their dynamical lifetimes appear too short (Morbidelli et al., 2000; Dauphas et al., 2000; Gomes et al., 2005b; Ipatov & Mather, 2007). Noble gas (Swindle & Kring, 2001) and other isotopes including <sup>15</sup>N/<sup>14</sup>N (Drake & Righter, 2002; Hutsemékers et al., 2009) provide further constraints.

Essentially, and with various caveats, incompatibility between typical D/H ratios in comets and Earth's SMOW is generally taken to exclude comets as the primary source of Earth's H<sub>2</sub>O, with a contribution of ~10% appearing probable (Morbidelli et al., 2000; Drake & Righter, 2002; Izidoro et al., 2013).

Nonetheless, isotopically similar Earth-ocean type water, found in the Jupiter-family comet 103P/Hartley 2 (Hartogh et al., 2011), suggests that its origin has not been fully resolved. At the same time, it is not evident that the SMOW D/H ratio is primordial, perhaps affected by biological and various chemical evolutionary processes (Izidoro et al., 2013).

**Delivery models** Chyba (1990) argued that the terrestrial planets acquired their water oceans, and other surface volatiles, through late-accretion of comets and carbonaceous asteroids during the Late Heavy Bombardment around 4 Ga (§12.6). He considered the competition between impact delivery of new volatiles and impact erosion of those already present (§11.4.5) and argued that, for the inner solar system planets, the net accumulation of water was favoured.

The contribution from primitive asteroids in the main asteroid belt has been constrained by both dynamical arguments (Morbidelli et al., 2000; Raymond et al., 2007a), timing of the associated water delivery compared with the time of terrestrial planet formation and collisional losses (Morbidelli et al., 2000; Genda & Abe, 2005; Canup & Pierazzo, 2006; O'Brien et al., 2006; Raymond et al., 2006c, 2007a, 2009c), and other isotopic ratios including <sup>187</sup>Os/<sup>188</sup>Os (Izidoro et al., 2013).

From dynamical models of the primordial evolution of solar system bodies, Morbidelli et al. (2000) found it plausible that the Earth has accreted water *throughout* its formation history, from the earliest phases when the solar nebula was still present, extending to the late stages of gas-free sweep-up of scattered planetesimals. They concluded that asteroids and comets from the Jupiter–Saturn region were the first water deliverers, when the Earth was less than half its present mass. The bulk of the water presently on Earth was subsequently carried by a few planetary embryos, originally formed in

the outer asteroid belt and accreted by the Earth during the final stages of its formation.

Finally in their chronology, and accounting for ≤ 10% of the present H<sub>2</sub>O, was the accretion of water-bearing comets from the Uranus–Neptune region and from the Kuiper belt. Simulations by Raymond et al. (2004, 2007a) gave somewhat comparable contributions from a few planetary embryos arriving stochastically, and from millions of planetesimals arriving in a more statistically robust manner.

The net result is that water on Earth would then have essentially the D/H ratio typical of that condensed in the outer asteroid belt. This is in agreement with the observation that the D/H ratio in the oceans is very close to the mean value of that of the H<sub>2</sub>O inclusions in carbonaceous chondrites (Lunine, 2006).

**Effects of planet migration** These models of H<sub>2</sub>O delivery assume that the giant planets maintained their orbits during the formation of the terrestrial planets.

Raymond et al. (2005a) found that the presence of an outer giant planet such as Jupiter does not enhance the H<sub>2</sub>O content of the terrestrial planets, but rather decreases both their formation and their H<sub>2</sub>O delivery time scale. The volume delivered is sensitive to the adopted orbital eccentricities of Jupiter and Saturn (O'Brien et al., 2006): the present eccentricities yield almost none, but with larger amounts delivered for the initially circular orbits predicted by the 'Nice model' (§12.6.3).

Significant H<sub>2</sub>O-delivery is also a by-product of the 'dynamical shake-up' model (Thommes et al., 2008c), and in the 'Grand Tack model' during the outward migration of Jupiter and Saturn (§12.6.4), in which H<sub>2</sub>O-rich bodies initially orbiting beyond Jupiter are scattered towards the inner solar system (Walsh et al., 2011; O'Brien et al., 2014). Detailed simulations are reported by Rubie et al. (2015).

**Terrestrial exoplanets** Similar simulations have been applied to exoplanet systems to assess their H<sub>2</sub>O-based habitability (e.g. Raymond, 2006; Ronco & de Elía, 2014). The latter used a disk surface density profile  $\propto r^{-\gamma}$ , replicating terrestrial-type planets with ocean masses 30–170  $O_{\oplus}$  for  $\gamma = 1$ , and 200–2300  $O_{\oplus}$  for  $\gamma = 1.5$ . Simpson (2017a) has argued that the fine balance in H<sub>2</sub>O-retention required to result in a planet surface maintaining extensive areas of land and water, 71% H<sub>2</sub>O-coverage in the case of Earth, points to substantial Bayesian evidence that anthropic selection effects are at work.

### 12.3.5 Plate tectonics

The theory of *plate tectonics* describes the large-scale evolution of the Earth's lithosphere over the last few hundred Myr. Accepted around 1960, it builds on the related concept of continental drift developed during the preceding decades.

<sup>5</sup>The Commission on Atomic Weights and Isotopic Abundances of the International Union of Pure and Applied Chemistry (IUPAC) recommends that H isotopic ratios are given relative to VSMOW, the Vienna Standard Mean Ocean Water, which itself superseded SMOW in 1993 (IUPAC, 1995). The Commission updates the *Table of Standard Atomic Weights* biannually.



**Late Accretion, Late Heavy Bombardment, and Late Veneer:** These are three different but related concepts characterising various events during the terminal stages of the Earth's formation, after core–mantle differentiation, and around the time of the Moon-forming impact. None appear uniquely associated with the origin of volatiles on Earth.

Growth of a planet like Earth is characterised by a sequence of giant impacts from planetary embryos (masses intermediate between Moon and Mars) and smaller planetesimal impacts (small asteroid-like bodies). *Late Accretion* describes the accretion tail occurring *after* the final giant impact, i.e. after lunar formation if the last giant impact is identified with the Moon-forming event (§12.3.3). A detailed timeline can be derived from lunar cratering (Morbidelli et al., 2012b; Morbidelli & Wood, 2015). Estimates of the total *late-accretion mass* are dependent on the impactor size distribution when scaling the lunar impact crater record to the (gravitational) cross section of the Earth, but are of order  $5 \times 10^{-3} M_{\oplus}$ .

In contrast to a simple exponential tail of impact events, evidence points to a surge in lunar impact frequency prior to formation of the crater Imbrium (Bottke et al., 2007). This surge is termed the *Late Heavy Bombardment* or *Lunar Cataclysm* (Bottke & Norman, 2017). Impact ages of lunar samples (Tera et al., 1974) and lunar meteorites (Cohen et al., 2000) indicate that impact rates were lower before 4.1 Ga than in the subsequent 3.9–3.7 Gyr period. Evidence for the impact clustering comes mainly, but not exclusively, from radiometric ages of impact melt rocks collected during the Apollo 15–17 missions (Tera et al., 1974), with the subsequent literature being substantial and somewhat discordant (e.g. Hartmann et al., 2000; Morbidelli et al., 2001; Strom et al., 2005; Bottke et al., 2007; Thommes et al., 2008a; Cuk et al., 2010; Zellner & Norman, 2012; Rickman et al., 2017; Michael et al., 2018). The surge is also consistent with a change in the orbits of the giant planets (Haghighipour & Scott, 2012; Bottke et al., 2012; Nesvorný et al., 2017), presently attributed to gas and/or planetesimal-driven migration, as described by the 'Grand Tack' and 'Nice' models, respectively (§12.6). While this appears the favoured explanation for the Late Heavy Bombardment, others have been considered (e.g. Levison et al., 2001a; Chambers, 2007; Brasser & Morbidelli, 2011).

The concept of a *Late Veneer* developed from the observed abundances of siderophile elements (§10.4.7) in the primitive upper mantle (or *bulk silicate Earth*). Broadly, noble metal concentrations are more depleted in the mantle than other siderophiles, but still far more abundant than expected from mantle–core equilibrium. The Late Veneer posits a small mass of chondrite-like material added to a post-core segregated mantle, never re-equilibrated with the core, although homogenised in the mantle by convection (Turekian & Clark, 1969; Kimura et al., 1974; Chou, 1978; Willbold et al., 2011; Brenan, 2012; Day et al., 2012; Schlichting et al., 2012; Rivera-Valentín & Barr, 2014; Rubie et al., 2015; Dale et al., 2017; Genda et al., 2017). The Late Veneer mass is estimated at  $5 \times 10^{-3} M_{\oplus}$  (Walker, 2009; Jacobson et al., 2014). Morbidelli & Wood (2015) suggest that the Late Veneer and Late Accretion are not the same events, although their associated masses may correspond within a factor 2.

Plate tectonics on Earth, in part driven by radiogenic heating (Walker et al., 1981), is considered as essential in modulating its atmospheric composition over geological time, and is thus commonly believed to be vital for planetary habitability at large. Detailed plate configuration is also believed to control the patterns of 'icehouse' and 'greenhouse' conditions on Earth over the past 1 Gyr (box, page 676). Mass redistribution in the convecting mantle leads to perturbations in its moment of inertia tensor, and to a change in direction of the rotation vector. Existence of this *true polar wander* is well established, although its rate and magnitude over geological time is not (Rose & Buffett, 2017).

Within the solar system, only Earth, but perhaps also Europa (Kattenhorn & Prockter, 2014), exhibits such plate tectonics.

**Carbonate–silicate cycle** Plate tectonics underpins the carbonate–silicate geochemical cycle. This involves the transformation of silicate rocks to carbonate rocks by weathering and sedimentation at the Earth's surface, and the transformation of carbonate rocks back into silicates by metamorphism and magmatism. This plays, in turn, a large part in the carbon cycle, since the equilibrium point of the carbonate–silicate cycle dictates the rate of carbon release from the lithosphere.

Specifically, atmospheric  $\text{CO}_2$  dissolves in rainwater, forming carbonic acid ( $\text{H}_2\text{CO}_3$ ), which slowly dissolves silicate rocks. These are carried to the ocean, where they are used by organ-

isms (such as foraminifera, radiolarians, and diatoms) to create shells of calcite ( $\text{CaCO}_3$ ) or opal ( $\text{SiO}_2$ ). When these die, some are re-mineralised, but some fall to the sea floor where they are buried, progressively subducted, and eventually re-form calcium silicates and release gaseous  $\text{CO}_2$  through volcanism.

**Structure** The Earth's *lithosphere*, its rigid outermost shell consisting of the crust and upper mantle, comprises 7–8 large plate-like regions, and a number of smaller plates. Tectonic plates move because the Earth's lithosphere has greater strength than the underlying high-viscosity *asthenosphere*. Where the plates meet, their relative motion determines the type of boundary: convergent, divergent, or transform. Earthquakes, volcanic activity, mountain-building, and oceanic trench formation occur along the plate boundaries. Annual relative movement of the plates is typically in the range 0–0.1 m.

Tectonic plates are composed of oceanic lithosphere and thicker continental lithosphere, each topped by its own kind of crust. Along convergent boundaries, subduction carries plates into the mantle, with material lost roughly balanced by new oceanic crust along divergent margins by seafloor spreading.

Lateral density variations in the mantle result in convection. Plate movement is thought to be driven by a combination of the motion of the seafloor away from the spreading ridge, and drag, with downward suction, at the subduction zones. Tidal forces of the Sun and Moon may contribute. The relative importance of each of these factors is still the subject of debate.

The likely inception of plate tectonics on Earth, and its subsequent evolution, is itself considered to be influenced by various factors: the relatively constant surface heat flux, the role of subduction of surface water, mantle dynamics, and the secular evolution of the atmosphere through sea-level changes caused by ocean–mantle interaction (Korenaga, 2013).

Table 12.3: Crustal abundance ratios by mass relative to Ca. The most pronounced chemical enrichment occurs for Ba in the Earth's continental crust, which may provide a proxy for the existence of plate tectonics on other planets, or in white dwarf photospheric debris. From Jura et al. (2014), Table 1.

Crust	Mg	Fe	Sr	Ba	Ref.
Earth – continental	0.62	1.1	7.0e-3	0.010	(1)
Earth – oceanic	0.62	0.89	3.0e-4	7.3e-5	(2)
Lunar highland	0.24	0.31	1.2e-3	6.1e-4	(3)
Mars	1.1	2.8	7.2e-4	1.1e-3	(3,4)
Vesta	0.58	2.0	1.0e-3	2.3e-4	(5)
CI meteorites	11	20	8.6e-4	2.5e-4	(6)

- (1) Rudnick & Gao (2003); (2) Taylor & McLennan (2009);  
 (3) Taylor & McLennan (2009); (4) (McSween, 1985);  
 (5) (Mittlefehldt, 2003) (6) Wasson & Kallemeyn (1988)

**Crustal composition** Internal melting and the subsequent differentiation into an Fe-dominated core, a Mg-elevated mantle and a Si-rich crust are central to the evolution of the solar system's rocky planets. Crusts are the most easily studied of these three zones, and they display a wide variety of compositions (Taylor & McLennan, 1995, 2009). While the crusts of other solar system objects are largely basaltic, Earth's continental crust is compositionally unique (Rudnick & Gao, 2003) because, as a consequence of plate tectonics, it is the product of partial melting of preexisting oceanic crustal material, itself basaltic, that results in significant enrichments in *incompatible elements* (in geochemistry, unsuitable in size and/or charge to the relevant cation sites) by magmatic distillation.

Detailed abundances of the crusts of four solar system bodies are available: Earth, Moon, Mars and Vesta (Taylor & McLennan, 2009). In all, the most abundant elements are O and Si, followed by Al and Ca. Because they are largely sequestered into the core and mantle, respectively, Fe and Mg are deficient.

Compared to basaltic crusts (Table 12.3), Earth's continental crust is compositionally unique, with 'incompatible' elements highly concentrated within the outermost zone containing only 0.6% of its mass (Rudnick & Gao, 2003). In one of the two groups of incompatible elements (the 'LILE' group) Ca, Sr and Ba have relatively large ionic radii that are accommodated by the more Si- and Al-rich tectosilicates that form from crystallisation of the partial melts of oceanic plate material. The most pronounced enrichment occurs for Ba, the largest atom. Table 12.3 includes abundances in CI chondrites, the approximate initial nebular composition before the rocky objects formed and evolved.

**Observational proxies and accretion signatures** In the crusts of the Moon, Mars and Vesta, Sr and Ba are at most modestly enhanced relative to Ca, while both are markedly enhanced in Earth's continental crust, and modestly depleted in its oceanic crust. The simultaneous substantial enhancements of  $n(\text{Sr})/n(\text{Ca})$  and  $n(\text{Ba})/n(\text{Ca})$  have been considered as serving as an observational signature of Earth-analogue plate tectonics in the accretion debris inferred from white dwarf photospheric abundances (Jura et al., 2014, see also §8.9.5).

**Relevance to exoplanets** The existence of plate tectonics has been inferred from planet-type accretion evidenced by white dwarf photospheric abundances (§8.9.5). Plate tectonics, as a criterion for habitability on other planets, is detailed further in Section 11.7.3.

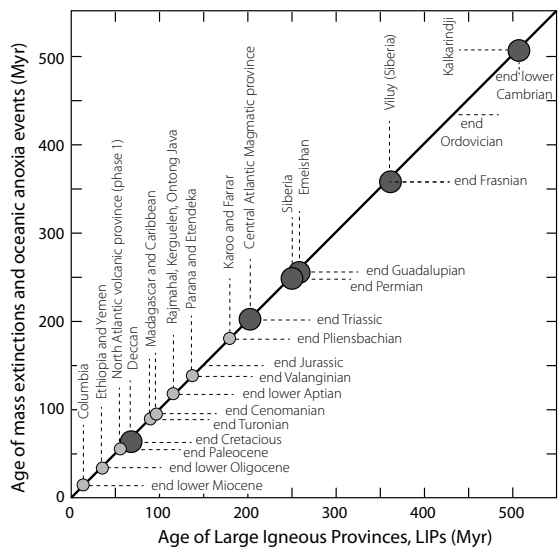


Figure 12.7: Correlation between the ages of mass extinctions and oceanic anoxia events (ordinate) with those of Large Igneous Provinces (LIPs, abscissa). Included in the latter are both Continental Flood Basalts (CFB) and Oceanic Provinces (OP). Ages are largely from Rampino & Stothers (1988), with uncertainties typically being smaller than the circle diameters. The largest recent mass extinctions and corresponding events are shown as larger circles. The figure is adapted from Keller et al. (2012, Figure 2), based on earlier versions by Rampino & Stothers (1988) and Courtillot & Renne (2003).

### 12.3.6 Volcanism and large igneous provinces

Relevant in the context of habitability or detectability are the geological phenomena of *large igneous provinces*, or LIPs, extremely large accumulations of (liquid or volcanic) igneous rock, occurring when hot magma extrudes from Earth's interior. Many if not all known large igneous provinces are attributed to mantle plumes or plate tectonics (Foulger, 2010; Platz et al., 2015). Rampino & Stothers (1988) cited eleven distinct flood-basalt episodes over the past 250 Myr which coincided with mass extinctions.

Subsequent work has confirmed the suggested correlation (Courtillot, 1994; Courtillot & Renne, 2003; Keller, 2005; Courtillot & Olson, 2007; Courtillot et al., 2010; Keller et al., 2012; Bond & Wignall, 2014), as shown in Figure 12.7. Protracted volcanism may also follow large impact events (Ubide et al., 2017).

Various studies into the likelihood and detectability of volcanic activity on exoplanets are being undertaken (e.g. Kite et al., 2009; Kaltenecker et al., 2010b; van Summeren et al., 2011; Misra et al., 2015). For example, Kite et al. (2009) estimate volcanism versus time for planets with Earth-like composition and masses in the range  $0.25 - 25 M_{\oplus}$ . They show that volcanism is likely to proceed on massive planets with plate tectonics over the main-sequence lifetime of the parent star.

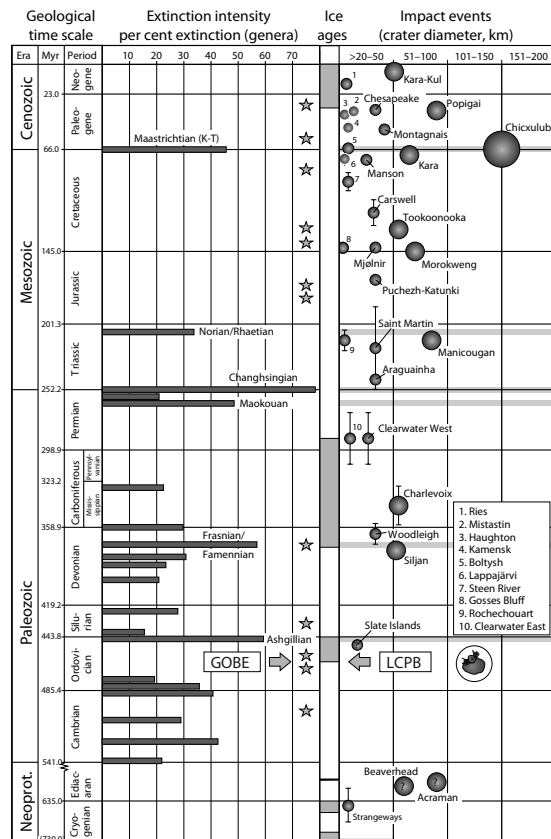


Figure 12.8: Mass faunal extinctions (left), major ice ages (centre), and impact craters (right) over the past 730 Myr. Stratigraphic subdivisions and ages are from the 2012 Geological Time Scale (Gradstein et al., 2012). Extinction events and intensities (above 15% intensity at genus level) are from Keller (2005). Ages and sizes of impact craters (>20 km) are from the Earth Impact Database (Table 1.4). The L-chondrite parent body breakup (LCPB, which led to many small craters) and the co-eval Great Ordovician Biodiversification Event (GOBE, representing evolutionary changes through much of the Ordovician) are shown at ca. 470 Ma, relating to one early major event in a chain of events. Large shaded 'stars' denote time windows for which the meteorite flux has been reconstructed. Originally appearing as Schmitz (2013, Figure 1), this revision dated 2017 December was provided by Birger Schmitz.

### 12.3.7 Impact events

A compilation of impact cratering events on Earth is maintained at the Earth Impact Database (Table 1.4). This was used as the basis of studies by Bailer-Jones (2011), and for the compilation shown in Figure 12.8.

In addition to the largest-known Vredefort and Sudbury craters at around 2 Ga, these impact structures include the Kara-Kul at ~5 Ma, the Popigai and Chesapeake Bay events at ~35 Ma, the Chicxulub at ~65 Ma, and the Morokweng at ~145 Ma. The three largest over the past 200 Myr, Popigai, Chicxulub, and Morokweng

(Figure 12.8) are presently considered to be H chondrite, CM chondrite, and LL chondrite respectively.

Although much is known about the population of potential impactors and cratering rates in the inner solar system at the *present* time (Michel & Morbidelli, 2007), asteroidal and cometary impact rates have likely varied over each Gyr interval (Shoemaker, 1998, Table 1). Determining whether individual craters are due to comets or asteroids is not straightforward, even on Earth.<sup>6</sup>

**Impact chronology** The Moon provides an archive of impact cratering in the solar system throughout the past 4.5 Gyr (e.g. Le Feuvre & Wieczorek, 2011; Rickman et al., 2014; Morbidelli & Wood, 2015; Fassett, 2016; Nesvorný et al., 2017; Rickman et al., 2017). It preserves this record better than the larger terrestrial planets, which have largely lost their ancient crusts through geological reprocessing and hydrospheric or atmospheric weathering (Joy et al., 2016).

Considerable bombardment evidence also occurs widely elsewhere, including on Mercury (e.g. Correia & Laskar, 2012; Marchi et al., 2013), Venus (e.g. Herrick & Rumpf, 2011), and Mars (e.g. Robbins & Hynek, 2012), as well as on numerous minor solar system bodies, including Pluto (Calandra & Gil-Hutton, 2017) and Ceres (Strom et al., 2018). Cratering on planetary surfaces provides the only technique for establishing their ages remotely (Fassett, 2016).

Basin magnetisation, crater-size distributions, and other proxies indicate that the last episode of heavy lunar bombardment ended about 3.85 Ga (box, page 669), with an impact flux that affected all of the inner solar system (Ćuk, 2012), possibly with a saw-tooth flux profile over the preceding 1 Gyr (Morbidelli et al., 2012b), and an extended tail thereafter (Kirchoff et al., 2013). Impact rates are affected by the planetary system architecture, with models suggesting that the  $\nu_6$  secular resonance (box, page 693) plays a particularly important role (Smallwood et al., 2018).

<sup>6</sup> An example of this complexity is offered by Chicxulub at the Cretaceous–Tertiary (K–T, or Cretaceous–Paleogene, K–Pg) boundary (for details, see Moore & Sharma, 2013). Alvarez et al. (1980) hypothesised the bolide to be a 6–14-km diameter asteroid. Studies in the 1980s suggested that it could be a comet or part of a comet shower, while modeling of the impact energetics could not definitively distinguish impactor type. A meteorite fragment in K–T boundary-age sediments in the Pacific, and Cr isotope anomalies, indicated that it was a carbonaceous chondrite, but not its origin. Absence of increased  $^3\text{He}$  across the K–T boundary suggested that the impactor was an asteroid or a single comet, rather than part of a comet shower. More recent studies of impact cloud dynamics and spherule formation are also unable to distinguish slow, rocky asteroidal impactors from faster, icy cometary impactors. Increasingly sophisticated simulations suggest that an asteroid 13 km diameter would be required to produce a 180 km crater, although estimates from background Ir fluence suggest a smaller impactor of 7 km.

**Extraterrestrial spinels:** Reconstructing paleo-variations in the flux of different meteorite types on Earth is challenging: meteorite falls are rare, they weather rapidly on the surface, and the direct cratering record is efficiently erased over time. Antarctica offers some of the most productive regions for collecting Earth-impact meteorites, particularly in the *meteorite stranding zones*, where upward-flowing ice combines with high ablation rates to concentrate large numbers of englacially transported meteorites at the surface (e.g. Evatt et al., 2016; Petersen et al., 2016).

Prospects have improved with the realisation, from studies of 462–466 Ma (mid-Ordovician) meteorites, that most of the *spinel group* of minerals, such as spinel ( $\text{MgAl}_2\text{O}_4$ ) and chromite ( $\text{FeCr}_2\text{O}_4$ ), are extremely resistant to weathering (Thorslund & Wickman, 1981), and can be recovered from slowly-formed sediments of almost any age over the past 3.5 Gyr (e.g. Schmitz, 2013). Once recovered, the spinel grains can provide considerable information on the original host meteorite. Methods have been developed for determining the class, group and petrologic type; noble-gas measurements provide the meteorite's cosmic ray exposure age, exposure of solar wind during transport to Earth, and regolith-derived gas signals acquired on asteroid parent bodies. In some spinel types, the cosmic ray tracks acquired in space, at a specific time in the history of the solar system, can be reconstructed.

Changes in the (micro-)meteorite flux, which may have a number of astronomical explanations, can then be tied in detail, bed-by-bed in the geological strata, to the evolution of life, and to the record of volcanism, climate and sea-level. An extensive discussion of the many prospects for this approach are given by Schmitz (2013).

In practice, almost all meteorite types contain a small fraction of spinels that survive weathering and can be recovered by acid-dissolution of large samples (100–1000 kg) of slowly-deposited sediments. The Astrogeobiology Laboratory in the Division of Nuclear Physics at Lund University (SWE), constructed in 2013, is currently dissolving 5–10 tonnes of limestone per year for recovery of extraterrestrial minerals, targeting the recovery of down to one spinel grain per 100 kg of rock (Schmitz, 2013). Results to date (cf. Figure 12.8) have focused on the collisional fragments from the L-chondrite parent body breakup (LCPB), the largest known asteroid disruption event in the past 3 Gyr (Schmitz et al., 2015, 2016, 2017; Boschi et al., 2017; Heck et al., 2017).

There is also a growing realisation that both pristine as well as fossil pseudomorphic micrometeorites can be recognised, and are likely common, within the geological record (e.g. Suttle & Genge, 2017).

Ongoing impacts provide constraints on the distribution of current impactor material. For the Moon, Madiedo et al. (2014) reported the largest detected on 2013 September 11 ( $M \sim 750$  kg,  $D_{\text{crater}} \sim 46$  m). Ongoing rates on Mars have been derived from pre- and post-impact imaging by the Mars Reconnaissance Orbiter (Malin et al., 2006; Daubar et al., 2013), and on Jupiter from atmospheric flashes (Hueso et al., 2013).

Condensed vapour *impact spherules* from the larger (> 10 km) impacts are preserved in the geological record, and provide further constraints on the past impactor

flux (Johnson & Melosh, 2012; Johnson et al., 2016a).

Another promising diagnostic is based on the direct recovery of spinel grains from slowly-formed sedimentary rocks of almost any geological age (box, page 672).

### 12.3.8 Atmosphere of the Earth

As an instance of terrestrial-type atmospheres (§11.4.3), the Earth's is considered to have originated principally as a result of accretion, with the capture of nebula volatiles probably having had a minor role (Lewis & Prinn, 1984; Zahnle et al., 2010, and references).

The Earth's atmospheric composition, and its evolution over time, have been estimated from three classes of models of relevance over successive epochs: those derived from planet formation models, those over geological time scales for which better observational constraints exist, and more recent and definitive constraints on gases and temperatures from ice-core records.

**Earth's early atmosphere** Zahnle et al. (2007) have proposed a possible time line of the early atmosphere, starting with the Moon-forming impact at about 4.6 Ga, and extending over the  $\sim 0.8$  Gyr of the Hadean (or pre-Archean) eon. The start of the Archean is characterised by the appearance of the geological record on Earth, at about 3.8 Ga.

Figure 12.9 illustrates their speculative narrative, as summarised by Zahnle et al. (2010). The earliest phase was probably marked by a hot silicate atmosphere that would have cooled and condensed over  $\sim 1000$  yr. Volatile elements were partitioned between the atmosphere and the mantle according to their solubility in the silicate melt:  $\text{H}_2\text{O}$  and S predominantly entering the mantle, with CO,  $\text{CO}_2$ , and other gases entering the atmosphere.

With the Moon-forming impact likely to have eroded a significant fraction of the atmosphere, but leaving much of the water (Genda & Abe, 2003, 2005), the subsequent cooling would have been controlled by the hot  $\text{H}_2\text{O}$  (steam) atmosphere. Fe sank through the mantle to the core, and the silicate/magma mantle solidified from the interior outwards over a period of  $\sim 2$  Myr. At this stage, the atmospheric gas composition was mostly (in decreasing fraction)  $\text{H}_2$ , CO,  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ , and  $\text{N}_2$ .

After solidification (freezing), the mantle would no longer convect as easily, the geothermal heat flow would have dropped, the runaway greenhouse atmosphere inhibited, and the steam rained out to form hot  $\text{H}_2\text{O}$  oceans with a high salinity due to the dissolved atmospheric NaCl. At this point, the surface temperature had dropped to  $\sim 500$  K, and the atmosphere contained  $\sim 1 - 2 \times 10^7$  Pa of  $\text{CO}_2$ .

The resulting  $\text{CO}_2$  atmosphere, liquid  $\text{H}_2\text{O}$  ocean, and basaltic surface crust formed an unstable combination (Urey, 1952), with the  $\text{CO}_2$  reacting to form carbonates and thereby removed from the atmosphere (Sleep

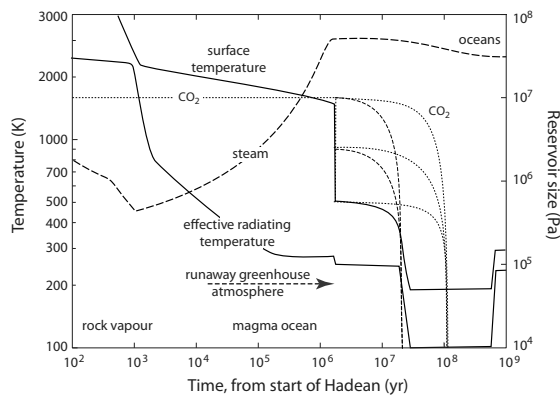


Figure 12.9: Energetically self-consistent schematic of the Earth's early atmosphere, showing the temperature,  $\text{H}_2\text{O}$ , and  $\text{CO}_2$  content during the Hadean, between 4.6–3.8 Ga (the start of the Hadean, beginning with the Moon-forming impact, is at the left). The phase of  $\text{CO}_2$  subduction is shown with an assumed time scale of 20 Myr (long dashes) or 100 Myr (short dashes). Adapted from Zahnle et al. (2010, Figure 3).

& Zahnle, 2001; Zahnle et al., 2007, their figure 11). Hydrothermal circulation through the oceanic crust on the sea floor, combined with rapid mantle turnover, may have subducted  $\sim 10^7$  Pa of  $\text{CO}_2$  from the atmosphere to the mantle in  $\leq 10$  Myr (Sleep, 2010).

Following the subduction of  $\text{CO}_2$ , and in the absence of another greenhouse gas, the Earth's surface in the late Hadean may have been very cold,  $\sim 220$  K, because of the lower luminosity of the young Sun. Thin ice-covered oceans may have had liquid water around volcanoes, with other liquid episodes following the hundreds or thousands of intermittent asteroid impacts continuing from the residual planetesimal accretion phase of the Earth's formation. These freezing pools, as sites of concentrated HCN and  $\text{H}_2\text{CO}$ , may have been favourable for the origin of life (Bada et al., 1994), perhaps accelerated by lightning (Chameides & Walker, 1981) or bolide impacts (Fegley et al., 1986; Chyba & Sagan, 1992).

**Evolution of  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{O}_2$**  A schematic of the relative concentrations of  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{O}_2$ , over the entire history of the Earth, is shown in Figure 12.10.

The Sun's luminosity at the time of Earth's formation,  $\sim 4.6$  Ga, was significantly lower than it is today, at around  $0.7L_\odot$ . Nevertheless, the fact that there is no evidence in the geological record for widespread glaciation until about 2.3 Ga, suggests that the Earth was probably warmer than it is today. This dichotomy is known as the *faint young Sun paradox*.

Greenhouse gases are held responsible for resolving this paradox, although problems in detailed modeling remain (e.g. Feulner, 2012; Kienert et al., 2012; Iorio, 2013; Wolf & Toon, 2013a,b; Le Hir et al., 2014).

Early ideas that  $\text{NH}_3$  was responsible (Sagan & Mullen, 1972) were revised when it became evident that

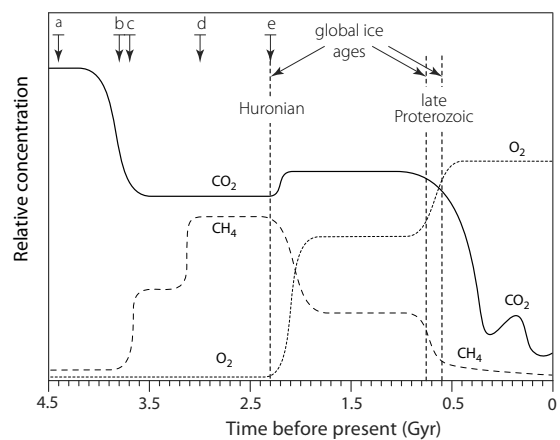


Figure 12.10: Relative concentrations of  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{O}_2$  over Earth's history. Key epochs are: (a) high concentrations of  $\text{CO}_2$  compensate for the lower luminosity of the young Sun; (b) the first microscopic life begins consuming  $\text{CO}_2$ ; (c) methanogens start to contribute to the atmosphere; (d) the appearance of  $\text{O}_2$ -producing bacteria; (e) the appearance of atmospheric  $\text{O}_2$ . The epoch of the origin of the  $\text{CH}_4$ -producing microbes is somewhat arbitrary. Adapted from Kasting (2004, Figure 3).

$\text{NH}_3$  would be rapidly destroyed by ultraviolet radiation in an  $\text{O}_2$ -free atmosphere. In consequence,  $\text{CO}_2$  was considered as the next most likely candidate (Wigley & Brimblecombe, 1981, and references).

This was in turn revised, in view of the absence of the mineral siderite, implying that  $\text{CO}_2$  concentrations were far lower than would be necessary to account for the required greenhouse warming (Rye et al., 1995). Methanogens,  $\text{CH}_4$ -producing microbes feeding directly on  $\text{H}_2$  and  $\text{CO}_2$ , have been hypothesised as being responsible for this period of greenhouse warming (Pavlov et al., 2000; Kasting & Siefert, 2002; Pavlov et al., 2003; Ueno et al., 2006), although microbial life-forms producing organosulphur-based compounds such as methanethiol ( $\text{CH}_3\text{SH}$ ) have also been considered (Pilcher, 2003). An *anti-greenhouse effect* caused by a high-altitude polymerised hydrocarbon haze, may have provided negative feedback to stabilise both atmospheric temperature and composition.

Evidence for progressive oxidation of Earth's atmosphere is well documented geologically, but the underlying causes remain uncertain. In the scenario described by Holland (2009), volcanic outgassing, in which the  $\text{H}_2/\text{H}_2\text{O}$  ratio has remained constant over time but where the  $\text{CO}_2/\text{H}_2\text{O}$  and  $\text{SO}_2/\text{H}_2\text{O}$  ratios have increased, combined with recycling of  $\text{CO}_2$ ,  $\text{SO}_2$ , and  $\text{H}_2\text{O}$ , can account for many of the major steps in its oxygenation (Figure 12.10). Holland (2009) details the relevance processes which may have operated during the *great oxidation event* around 2.4 Ga (Holland, 2002, 2006; Westall et al., 2012), and the long period of redox stability between 1–2 Ga (the 'boring billion'). De-

tailed models of the early atmosphere and biosphere of Earth-analogue planets, employing a coupled atmospheric/biogeochemical model, are given by Gebauer et al. (2017). Mixing, CH<sub>4</sub> fluxes, ocean solubility, and mantle/crust properties are shown to strongly affect net primary productivity and surface O<sub>2</sub> fluxes.

**Snowball Earth** Rising O<sub>2</sub> levels, and the emergence of cyanobacteria and the destruction of CH<sub>4</sub> (Cloud, 1972; Farquhar et al., 2000, 2001; Pavlov et al., 2001a; Falkowski, 2005; Raymond & Segrè, 2006), are believed to have led to a significant drop in global temperatures and the emergence of a ‘snowball Earth’, firstly at around 2.3 Ga (the Huronian glaciation) and, subsequently, the late Proterozoic glaciations ~750 and 600 Ma (e.g. Schrag et al., 2002; Hoffman & Schrag, 2002).

The subsequent intervals of ‘icehouse’ and ‘greenhouse’ Earths appear to be primarily linked to plate tectonic processes (box, page 676) which, in turn, have a more general bearing on whether exoplanets in the potentially habitable zone actually possess liquid water.

**The Phanerozoic** Better geological constraints on the CO<sub>2</sub> and O<sub>2</sub> atmospheric concentrations are available since the start of the Phanerozoic eon (e.g. Berner & Kothavala, 2001; Berner, 2001, 2006). As the current eon in geological time scale, its beginning, at around 540 Ma (starting with the Paleozoic era and, within that, the Cambrian period), was marked by the appearance of diverse hard-shelled animals.

The Geocarb III model of Berner & Kothavala (2001), and the Geocarbsulf model of Berner (2006) are widely-referenced models for the long-term cycles of C, and C+S, respectively, including effects of feedback, weathering, and degassing. The Geocarb III results were used, for example, for the paleoclimate synopsis in the 2007 Report of the Intergovernmental Panel on Climate Change (Solomon et al., 2007). In these models there are three major C sinks: the atmosphere, ocean, and rock (lithosphere), with C moving in and out of each. Atmospheric CO<sub>2</sub> concentrations are currently 300 ppm, a factor 8 less than in the (warm) late Cretaceous. CO<sub>2</sub> is the major factor controlling Earth’s temperature over the past 2 Gyr.

Resulting models demonstrate a generally decreasing concentration of CO<sub>2</sub> (Figure 12.11a), but with a broad minimum around the Carboniferous–Permian periods, and a peak at the Permian/Triassic boundary. Anthropogenic interference, while accelerating climate change through increased CO<sub>2</sub> to levels not experienced in the past few Myr, is driving Earth’s towards its more ‘natural’ state of greenhouse climate.

Atmospheric O<sub>2</sub> (Figure 12.11b) shows a broad late Paleozoic peak with a maximum value of about 30% in the Permian, a secondary peak centred near the Silurian/Devonian boundary, variation between 15–20% during the Cambrian–Ordovician, a sharp drop from 30% to 15% at the Permian/Triassic boundary, and a steady rise in O<sub>2</sub> from the late Triassic to the present.

Concentrations of ≥ 12% are considered to be the minimum necessary to support the forest fires evident in the geological record (e.g. Chaloner, 1989; Wildman et al., 2004; Scott, 2000). The O<sub>2</sub> curve may be a contributing factor to animal gigantism during the Permian–Triassic (Graham et al., 1995), to extinction at the Permian/Triassic boundary (Huey & Ward, 2005), and to mammalian evolution (Falkowski et al., 2005).

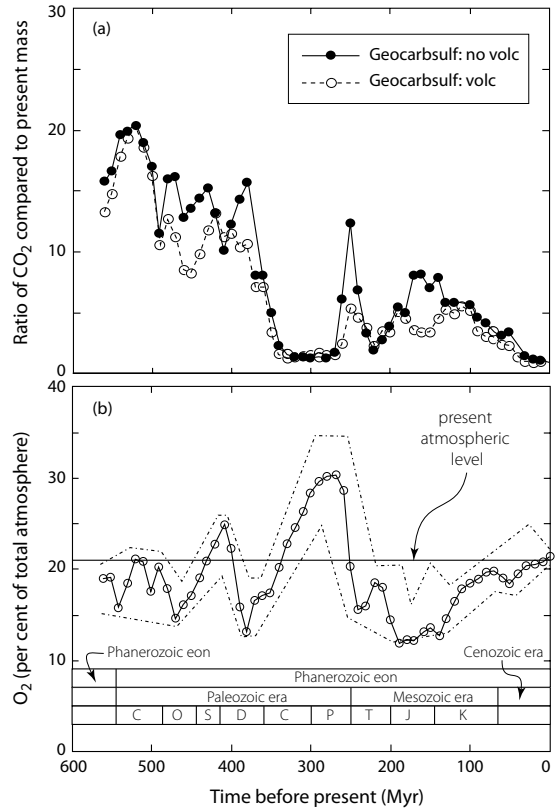


Figure 12.11: Atmospheric levels of CO<sub>2</sub> and O<sub>2</sub> during the Phanerozoic eon (from ~540 Ma to the present time): (a) ratio of CO<sub>2</sub> atmospheric mass compared to the present (the weighted mean for the past 1 Myr) from the Geocarbsulf model of Berner (2006). The terms ‘volc’ and ‘no volc’ refer to the inclusion, or not, of variable volcanic weathering. (b) O<sub>2</sub> abundance, as a percentage of the total atmospheric mass, also from the Geocarbsulf model. Dashed lines indicate estimated error ranges. Letters in the lower row signify the geological period. Adapted from Berner (2006, Figures 18 and 20).

**Ice-core records** Constraints on recent atmospheric properties and chemical compositions, via direct measurements of gases and temperature proxies, come from ice-core records. Antarctic samples extend back to 0.42 Ma for the 3700 m Vostok station programme (e.g. Petit et al., 1999; Bender, 2002; Kawamura et al., 2007; Juselius & Kaufmann, 2009), and 0.8 Ma for the 3200 m EPICA at Dome C (Wolff et al., 2010).

**Growth and patterns in biodiversity** Earth’s atmospheric evolution is closely linked to the widely-researched topics of the origin and evolution of life on Earth, including the explosive biodiversity during the Phanerozoic (e.g. von Bloh et al., 2003a), and the various extinction events.

Some of the oldest evidence for life is found in rocks from Australia dating to at least 3.5 Ga (Schopf, 1993). The growth in the diversity of genera versus time, based on the first and last stratigraphic appearance of 36 380 marine genera compiled by Sepkoski (2002), is shown in Figure 12.12. In their analysis, Rohde & Muller (2005) identified a 62 ± 3 Myr cycle, possibly correlated with the five great extinctions (Raup & Sepkoski, 1982).

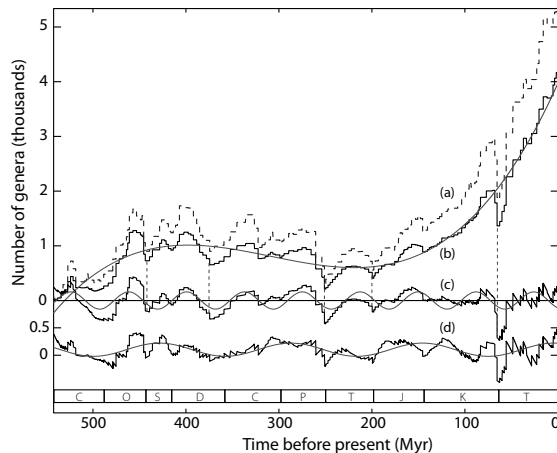


Figure 12.12: Diversity of marine genera during the Phanerozoic, from an analysis of the compendium of Sepkoski (2002) by Rohde & Muller (2005): (a) illustrates the rapid growth since the Cretaceous period ('K' in the period symbols at bottom); (b) the same data with single occurrence and poorly-dated genera removed; (c) after subtraction of the trend line shown by the smooth curve in (b), and with a 62 Myr sine wave superposed; (d) after removal of the 62 Myr cycle, and with a 140 Myr sine wave superposed. Dashed vertical lines indicate the times of five major extinctions. From Rohde & Muller (2005, Figure 1), by permission from Nature/Springer/Macmillan Ltd, ©2005.

Various studies over the past few decades have proposed a causal connection between terrestrial mass extinctions, climate change, and the motion of the Sun through the Galaxy. Proposed mechanisms include various effects attributable to the Sun's passage through the Galactic mid-plane, changes in cosmic rays and supernovae modulated by the passage of the Sun through the Galactic spiral arms, and enhanced comet impacts via perturbation of the Oort cloud due to the passage of nearby stars. Supposed periodicities in the fossil record and impact cratering dates are often cited as supporting these hypotheses, but the topic remains controversial. These various mechanisms, and the related statistical analyses, are considered further in Section 12.1.6.

### 12.3.9 Disruptive events on Earth

The highly varying conditions on Earth since its formation provide pointers to the interpretation of exoplanet habitability, or the development of (intelligent) life. Various dramatic environmental changes have occurred over its history, some of which have been linked to marked extinction events.

Amongst these are: variations in  $\text{CO}_2$ , the major factor controlling temperature over the past 2 Gyr (§12.3.8); semi-erratic periods of icehouses and greenhouses (box, page 676); geomagnetic field reversals (box, page 663); local supernovae (§12.1.2); volcanism and large igneous provinces (§12.3.6); and impact events (§12.3.7), perhaps related to the Sun's passage through the Galactic mid-plane or the approach of nearby stars (§12.1.6).

**Paleocene–Eocene thermal maximum** The Paleocene–Eocene Thermal Maximum (PETM) marked the abrupt boundary between the Paleocene and Eocene epochs at 55 Ma (McInerney & Wing, 2011). Global temperatures rose, over  $\sim 1000$  yr, by 5 C on average (to some 7–8 C warmer than today). The conditions persisted for  $\sim 100\,000$  yr, with the sea surface in the Arctic being as warm as the present subtropics, widespread extinctions, changes in ocean currents, less oxygen in the sea, and a decrease in carbonate  $^{13}\text{C}/^{12}\text{C}$  ratios. The rise has been attributed to an increase of atmospheric  $\text{CO}_2$  and  $\text{CH}_4$  (a total of some  $2 - 7 \times 10^{15}$  kg C, compared with the present anthropogenic  $4 \times 10^{12}$  kg  $\text{yr}^{-1}$ ), probably in two pulses (Bowen et al., 2014), and perhaps initiated by volcanic activity (e.g. Gutjahr et al., 2017). It has been the subject of considerable geoscience research over the past 20 yr, as an analogue for understanding global warming, and insight into the carbon cycle, climate system, ocean acidification, and biotic response (e.g. McInerney & Wing, 2011; Royer, 2016).<sup>7</sup>

**Effects on evolution** In addition to drastically reducing biodiversity, large meteoritic impacts may have contributed to conditions for life to appear (Véronique et al., 2012). As an example of other significant evolutionary changes, the Paleocene–Eocene Thermal Maximum was accompanied by a mass extinction of 35–50% of benthic foraminifera over  $\sim 1000$  yr, large-scale migration, while many major mammalian orders, including horses and primates, appeared and spread around the Earth over the subsequent 10–20 000 yr (Secord et al., 2012). Similarly, it has been conjectured that at the height of the last glacial maximum, or elsewhere in the past 2.7 Myr, environmental changes may have occurred with such stress levels that natural selection could have been driven, more rapidly than normal, towards increasing brain size, developing a hunter–gathering society, and the requirements and ability to work together, with the roots of human evolution perhaps to be found not in warmth or in cold, but in enhanced climatic variability.

## 12.4 Orbits

### 12.4.1 Ephemerides

Precision ephemerides of the Sun, the planets, Pluto, and the Moon, are given by the Development Ephemerides (DE) models of JPL, and the INPOP models of IMCCE.

Used for spacecraft navigation and astronomy, and as the basis of the *Astronomical Almanac*, these are presented as barycentric rectangular coordinates (ICRF; box, page 86) providing positions, velocities and accelerations at equally spaced intervals over a specified period. They take account of all available knowledge of properties including masses, solar oblateness, and relativistic corrections.

<sup>7</sup> For this and many other geological/climate projects, five successive international deep-sea drilling programmes have collected  $\sim 400$  km of core samples: Project Mohole in the 1960s, the Deep Sea Drilling Project (1968–1983, 97 km), the Ocean Drilling Program (1985–2003, 223 km), the Integrated Ocean Drilling Program (2003–2013, 57 km), and the International Ocean Discovery Program (2013–2023, 34 km). The latter included Expedition 360 to sample the mantle for the first time, and Expedition 364 to sample the Chicxulub impact crater.

**Icehouses, ice ages, and greenhouses:** The term ‘ice age’ is an early 20th century term reflecting the belief that there had been only one or two substantial glaciations in Earth’s history, and in the relatively recent geological past. It is now accepted that there have been five intervals in its 4.5 Gyr history, referred to as *icehouse Earths*, which have been conducive to the growth of ice at the poles (e.g. Frakes et al., 1992). In aggregate, icehouse conditions have persisted over some 15% of Earth’s history, and stand in contrast to *greenhouse Earth* conditions, with no persistent ice, occupying the remaining 85%.

Two of these five icehouses occurred during the pre-Cambrian supereon, viz. before the beginning of the Cambrian period about 540 Ma. The second of these, the Cryogenian period (720–635 Ma, just before the emergence of the small shelly fauna), included the Sturtian and Marinoan glaciations, the greatest known to have occurred on Earth (Pierrehumbert et al., 2011; Voigt et al., 2011; Abbot et al., 2012). Ongoing debate centres on whether these glaciations covered the entire planet (the so-called *snowball Earth*), or if a band of open sea survived near the equator (the ‘slushball Earth’). Mean surface temperatures of ~5 C were some 9 C below present levels, with atmospheric O<sub>2</sub> around 60% of modern levels, and CO<sub>2</sub> of ~1300 ppm, roughly 5 times pre-industrial levels.

Other icehouses occurred during the Ordovician period (400 Ma), primarily evidenced today in the Sahara (when present Africa was over the south pole); the substantial Permo–Carboniferous 80 Myr-duration Gondwana icehouse, which was restricted to the southern hemisphere and coincided with the merged landmasses of today’s southern hemisphere moving across the south pole; and the present Cenozoic era glaciation, which started about 40 Ma in the Antarctic, with ice caps developing in the Arctic some 2 Ma.

Superimposed on these five major icehouse periods have been hundreds of intervals of shorter duration, designated as *glacials* and *interglacials*, with ice on one or both poles, occurring on time scales of hundreds of thousands of years, and at still higher frequencies, the *stadials* and *interstadials* occurring on time scales of tens of thousands of years. The primary causes of these glacial and interglacial modulations are variations in insolation due to Earth’s orbit (the Milankovitch cycles; footnote, page 681). These orbital modulations of incident solar energy are not themselves the *cause* of icehouses, but rather are manifested as shorter period fluctuations when conditions are already suited for an icehouse Earth.

In the past 2.7 Myr of the late Cenozoic glaciation there have been hundreds of ice ages. During the Last Glacial Maximum, ~18 ka, ice sheets extended over much of north America and Europe, and sea levels (inferred from coral reefs) were some 100 m lower than today. During the last interglacial peak, some 125 ka, sea levels were some 5–6 m higher than today. Such findings resulted from the major NSF funded CLIMAP project of the 1970s and 1980s to produce a map of climate conditions during the Last Glacial Maximum and the previous interglacial (e.g. Yin & Battisti, 2001).

Direct geological evidence for ice ages includes the occurrence of glacial moraines and the resulting tillite rock types, as well as gouged glacial striations on rock platforms (Frakes et al., 1992). More complete and continuous paleoceanographic records of sea surface temperatures comes from various geochemical proxies from sediments built up on the ocean floor (e.g. Veizer et al., 2000; Lisiecki & Raymo, 2005), including the species composition of planktonic foraminifera assemblages, the variable <sup>18</sup>O/<sup>16</sup>O isotope ratio observed in the micro fossil CaCO<sub>3</sub> shells of amoeboid protozoa foraminifera, and Mg–Ca paleothermometry. The observed oxygen isotope ratio, for example, depends both on the ambient water temperature, as well as the water isotope ratio as fractionated by evaporation, whereby the water falling as ice on the poles is enriched in the lighter <sup>16</sup>O isotope, while the sea water itself is enriched in the heavier <sup>18</sup>O isotope.

The onset of icehouse conditions on Earth are generally, at least more recently, linked to two plate-tectonic processes (Smith & Pickering, 2003): the movement of continents into polar latitudes providing an accretion platform for the ice, and the closing of low-latitude oceanic gateways resulting in their thermal isolation from the warmer equatorial regions. A changing balance between the quantity of falling and melting snow, typically initiated by decreasing CO<sub>2</sub> levels, itself possibly due to lower volcanic activity, creates a positive feedback due to the high albedo of snow and ice, and a very gradual rather than precipitous evolution into icehouse conditions. For example, the current Cenozoic glaciation developed over some 40 Myr, with fully-developed glacial and interglacial cycles occurring only over the past 2.7 Myr (DeConto & Pollard, 2003).

An alternative explanation for the onset of icehouse conditions invokes the facts that more remote events are progressively harder to correlate with tectonic processes, while onsets within the past 200 Myr appear correlated with the (multiple) impactors of the late Devonian and end Eocene (Chesapeake/Popigai). These have led Schmitz (2013) to suggest a correlation with impact events, perhaps associated with re-alignment of Earth’s orbital elements. More speculatively, a relation between icehouse epochs and the Sun’s passage through the Galactic spiral arms, mediated by increased star formation, higher cosmic ray flux, and an increase in cloud cover, has been conjectured (§12.1.6).

Emergence from the major icehouses is believed to result from increasing atmospheric CO<sub>2</sub>, evident in the corresponding geological records, through increasing volcanic activity itself attributed to *continental rifting*, as continental plates diverge (Spicer & Corfield, 1992; McKenzie et al., 2016).

Observational data used in the fits (e.g. Folkner et al., 2014; Fienga et al., 2014, 2015) include transit and CCD observations of planets and small bodies, lunar laser-ranging, radar-ranging, distances measured by radio signals from spacecraft, 2d positional elements on the plane of the sky by VLBI of spacecraft, and planetary flybys and orbiters including Messenger (Mercury), Venus Express, Mars Odyssey, and Cassini (Saturn). The latter

also gave improvement in the orbits of Jupiter, Uranus, and Neptune (Hees et al., 2014).

The latest (major) updates are DE430 (Folkner et al., 2014), and INPOP 13 (Fienga et al., 2014, 2015). Indicative accuracies are ~0.001 arcsec for the inner planets (corresponding to ~1 km at the distance of Mars), and some 0.1 arcsec for the outer planets.



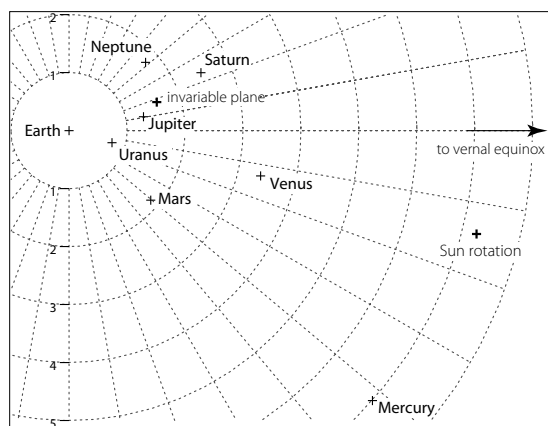


Figure 12.13: Relative positions of the angular momentum vectors for the orbits of solar system planets (orbital elements from Murray & Dermott 2000), along with that for the Sun's rotation (Seidelmann, 1992) and the solar system invariable plane (from Cox 2000), in J2000 ecliptic coordinates. From Barnes et al. (2011b, Figure 1), by permission of IOP Publishing/AAS.

#### 12.4.2 Orbits and angular momentum

**Eccentricities and inclinations** The low eccentricities and inclinations of the terrestrial planets provide a specific constraint for the core accretion model of the gas giants, and appear to be well described by current migration models (§12.6), as well as being specifically considered in the context of sweeping secular resonances (§12.6.1). They also appear to be typical when compared with eccentricities determined from radial velocity (§2.10.4) and transit measurements (§6.26.2), which suggest that higher eccentricities are found for single planet systems, with progressively lower eccentricities found for higher planetary multiplicities (e.g. Limbach & Turner, 2015; Martin & Livio, 2015; Xie et al., 2016).

**Angular momentum** The orbits of the solar system planets lie close to the same plane. Their mean inclination to the *invariable plane* (viz., the plane passing through its barycentre and perpendicular to its total angular momentum vector; Souami & Souchay 2012) is  $\langle i \rangle \approx 2^\circ$ . Excluding Mercury, the mean is  $\langle i \rangle \approx 1.5^\circ$ , and similar to a Rayleigh distribution of width  $\sigma_i \approx 1^\circ$  (Lissauer et al., 2011b). Relative positions of the angular momentum vectors of the solar system planets, along with that for the Sun's rotation and the solar system invariable plane, are shown in Figure 12.13.

#### 12.4.3 Resonances

Various orbital resonances in the solar system are summarised in the box, page 678. Examples of all types are already known, or inferred, in multiple exoplanet systems (§2.12), including the first example of a three-body Laplace resonance in the case of GJ 876 (Figure 2.42).

#### 12.4.4 Orbit stability and chaos

General considerations on the orbital stability of multiple planetary system, including the concepts of stability and chaos, with examples from long-term integrations of the solar system (including chaotic episodes in the orbits of the inner planets), have been described in §10.9.4.

The more rapid the planet's orbital movement, the finer the time step needed to integrate its motion over longer time intervals. Limited by computational power, until 1991 the only realistic numerical integration of the full solar system was the JPL ephemeris DE102, spanning 1411 BC to 3002 AD (Newhall et al., 1983).

Although very long-term numerical integration of planetary orbits can be used to identify domains of stability and chaos, detailed results are very sensitive to initial conditions and masses. Certain broad features were already identified in early studies, including the 100 Myr of the LONGSTOP outer planets project (Nobili, 1988; Roy et al., 1988; Milani et al., 1989); the 200 Myr of the MIT project (Applegate et al., 1986); the 845 Myr of the Digital Orrery (Sussman & Wisdom, 1988); the 1 Gyr of the first symplectic integration (Wisdom & Holman, 1991); and up to 5 Gyr in more global terms (Laskar, 1994, 1996; Laskar & Robutel, 2001).

LONGSTOP, for example, already identified long-period variations in the semi-major axes of the outer planets with periods of  $\sim 1$  Myr (Nobili, 1988). For Pluto, Milani et al. (1989) used a 100 Myr integration to confirm the 3:2 mean motion resonance with Neptune, a 19 900-year longitude libration, and a 3.78 Myr libration of its argument of pericentre. Its orbit is chaotic, with a Lyapunov exponent of  $1/(20 \text{ Myr})$  (Sussman & Wisdom, 1988), although its small mass means that its chaotic orbit has negligible consequences on the other planets. The latest symplectic integrations have been used to compute the evolution of Pluto's orbital elements over 500 Myr (Hernandez & Dehnen, 2017).

Both Sussman & Wisdom (1992) and Laskar (1994, 1996) found that, over Gyr, the inner solar system is chaotic, showing large orbital diffusion, and a Lyapunov exponent of  $1/(5 \text{ Myr})$ . The chaotic behaviour originates from two secular resonances, one related to the perihelia and nodes of Mars and Earth, the other to those of Mercury, Venus and Jupiter. Variations of the eccentricities and inclinations are evident over periods of a few Myr (Figure 12.14), behaviour known qualitatively to Laplace and Leverrier (as reported by Laskar, 1992).

The chaotic nature of the solar system orbits suggests the relevance of a statistical approach, in which the time-dependent position and velocity of the planets are replaced by the probability density function of their orbital elements, considered in the framework of statistical mechanics by Mogavero (2017).

**Escapes and collisions** In the simulations of Laskar (1994, 1996), Mercury's eccentricity reaches  $e \sim 0.5$  at

**Solar system resonances:** A substantial advance in the knowledge of the solar system over recent years has revealed more than 300 planetary satellites (counting some 200 for Saturn), many tens of thousands of asteroids with established orbits (and of various classes), as well as comets and Edgeworth–Kuiper belt objects. Complex ring systems are now known to accompany all of the giant planets (§12.5.12). Their collective physical structure and dynamical behaviour are determined by gravitational forces, and sculpted by the complex phenomenon of resonance (Peale, 1976). Some examples follow.

*Spin–orbit resonance:* most major satellites are in a 1:1 (or synchronous) spin–orbit resonance, in which the orbital period is equal to the rotation period. It is the end result of retarding torques on a circular orbit, and results (for example) in the same face of the Moon being always directed towards the Earth (§12.3.3). Other states are possible (§10.11.5): the unexpected 3:2 spin–orbit resonance of Mercury around the Sun was discovered by radar observations (Pettengill & Dyce, 1965), and explained in terms of its unusually large eccentricity ( $e = 0.21$ ) combined with its limited rigidity (Peale & Gold, 1965; Lemaître et al., 2006). However, Correia & Laskar (2012) found that the Mariner 10 and Messenger fly-by images reveal impact structures consistent with a primordial synchronous rotation, driven into the higher resonance state by collisions.

*Mean motion resonance:* this important class of orbit–orbit coupling occurs when two bodies have orbital periods (or mean motions, as defined by Equation 2.8) in a simple integer ratio. Qualitatively, stable orbits result when the two bodies never closely approach. Examples in the solar system include the stable orbit of Pluto and the Plutinos, despite crossing the orbit of Neptune, because of the 3:2 Neptune–Pluto resonance; and the Trojan asteroids, preserved by a 1:1 resonance with Jupiter. Several pairs of solar system satellites occupy mean motion resonances (Luan & Goldreich, 2017), notably Io–Europa, Europa–Ganymede, Enceladus–Dione, Mimas–Tethys, and Titan–Hyperion. Examples of unstable resonances include: (a) the largely empty lanes in the asteroid belt, the Kirkwood gaps; these correspond to mean motion resonances with Jupiter (most prominently at the 4:1, 3:1, 5:2, and 2:1 Jovian resonances), in which almost all asteroids have been ejected (while there are asteroid concentrations at the 3:2 and 1:1 resonances); (b) resonances between Saturn and its inner satellites, giving rise to gaps in the rings of Saturn; (c) the 1:1 resonances between bodies with similar orbital radii causing large solar system bodies to ‘clear out’ the region around their orbits by ejecting nearly everything else around them; this effect was incorporated into the IAU 2006 definition of a planet (§1.5).

*Laplace resonance:* this is a specific case of mean motion resonance, known to Laplace, which occurs when three (or more) orbiting bodies have a simple integer ratio between their orbital periods. Jupiter’s inner satellites Ganymede, Europa, and Io are in a 1:2:4 Laplace resonance, with Ganymede completing 1 orbit in the time that Europa makes 2, and Io makes 4. Their mean motions (Equation 2.8) are related by  $n_I - 3n_E + 2n_G = 0$ , satisfied to nine significant figures (Peale, 1976).

*Secular resonance:* a secular resonance occurs when one of the eigenfrequencies of the perturbing system is in a simple numerical ratio with the rate of change of the (proper) longitude of pericentre or the (proper) longitude of the ascending node (Murray & Dermott, 2000, Section 7.11). The consequence is that a small body in secular resonance with a much larger one will precess at the same rate, steadily changing its eccentricity and inclination. An example is the secular resonance between asteroids and Saturn. Asteroids which approach it have their eccentricity slowly increased until they become Mars-crossers, at which point they are usually ejected from the asteroid belt due to a close encounter with Mars. Secular resonances can also occur for a combination of three or more objects, relevant in the context of sweeping secular resonances (§12.6.1).

*Lidov–Kozai resonance:* this is experienced by bodies on highly inclined orbits, in which inclination and eccentricity oscillate synchronously, i.e. one increasing at the expense of the other, whilst conserving the quantity  $H_K = \sqrt{(1-e^2)} \cos i$  (Kozai, 1962). One consequence is the absence of bodies on highly-inclined orbits, since their growing eccentricity would result in a small pericentre, and leading to collision or destruction by tidal forces. Further details are given in Section 10.10.6.

The *Cassini state* is an evolved dynamical/rotational state in which the spin axis, orbit normal, and normal to the invariable plane (itself normal to the system’s total angular momentum vector) are co-planar, while the obliquity remains constant (Colombo, 1966; Peale, 1969). The result is a 1:1 secular spin–orbit resonance in which precession of the spin axis follows precession of the orbit axis. Cassini state 1 has both spin axis and orbit normal on the same side of the normal to the invariable plane, and conversely for state 2. Various instances occur in the solar system, including Mercury (Colombo, 1966; Yseboodt & Margot, 2006), the Moon, whose orbit around Earth precesses rapidly due to solar perturbations, and is tidally damped to Cassini state 2, although it may have occupied state 1 during its early history (Ward, 1974, 1975), Titan and Iapetus (Ward, 1975), Saturn (Ward & Hamilton, 2004), and Jupiter’s Galilean satellites (Bills, 2005). Persistent tides resulting from the non-zero obliquity have been considered but excluded as the primary heat source in Enceladus (Baland et al., 2016).

some epochs. While insufficient to cross the orbit of Venus, even small changes in the initial position of Earth, of  $\sim 150$  m, can lead to orbits in which Mercury escapes from the system or collides with Venus (see also Laskar, 2008; Laskar & Gastineau, 2009; Lithwick & Wu, 2011; Xu et al., 2011; Boué et al., 2012b; Lithwick & Wu, 2014). Similar escape solutions exist for Mars. Although escapes occur with only low probability, consistent with their continued existence, they demonstrate that the solar system is not strictly stable.

Extreme sensitivity to initial conditions in dynamical phase space extends to higher-order effects. Varadi et al. (2003) and Laskar & Gastineau (2009) carried out long-term numerical integration of the equations of motion which include contributions from the Moon, and adjustments due to general relativity. While still resulting in some solutions in which Mercury collides with Venus, the latter simulations also reveal solutions in which a decrease in the eccentricity of Mercury induces a change of angular momentum from the giant planets that desta-

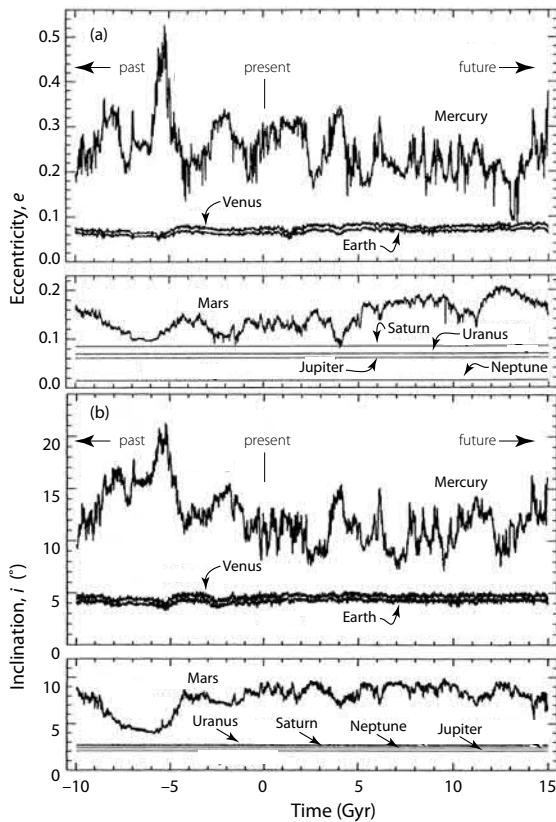


Figure 12.14: Numerical integration of the orbits of the solar system planets, 10 Gyr into the past and 15 Gyr into the future, showing (a) eccentricities, and (b) inclinations with respect to the J2000 ecliptic, each separated into two panels for clarity. For each planet, values plotted are the maxima over 10 Myr. The inner planets (especially Mercury and Mars) show large and irregular variations, while the giant planet orbits (Jupiter, Saturn, Uranus, Neptune) are far more regular. From Laskar (1994, Figure 1), reproduced with permission © ESO.

bilises all of the terrestrial planets  $\sim 3.34$  Gyr from now, with possible collisions of Mercury, Mars, or Venus with the Earth. Effects of gravitational waves are small but still present (Ismail, 2011).

**Earth's orbital history** The latest orbital solution for the long-term motion of the Earth, La2010 (Laskar et al., 2011a), spans from 0 to  $-250$  Myr, rapidly degrading in accuracy beyond  $-50$  Myr due to chaotic behaviour, such that geological data are now required to discriminate between earlier predictions. Due to chaotic behaviour imposed by past interactions between Earth and the main asteroids, including Ceres and Pallas, Laskar et al. (2011b) concluded that *'it will never be possible to recover the precise evolution of Earth's eccentricity beyond  $-60$  Myr'*. Before this, Earth collisions with Ceres and Vesta have a probability of  $0.2\%$   $\text{Gyr}^{-1}$ .

**Marginal stability** Despite the sensitivity to initial conditions, the fact that strong instabilities (collision or escape) occur only on time scales comparable to its age, i.e. of order 5 Gyr, implies that the solar system can be considered as marginally stable. The same simulations also show that the inner solar system is dynamically full, in the sense that any test objects introduced escape on time scales  $\ll 5$  Gyr. This dynamical filling has also been noted for many multiple exoplanet systems (§2.12).

The outer solar system is very stable (Figure 12.14), and also dynamically full (Gladman & Duncan, 1990; Holman & Wisdom, 1993; Levison & Duncan, 1993; Ito & Tanikawa, 2002).

**Implication for exoplanets** One general conclusion from these types of simulation is that the solar system, at the end of its formation, was most probably significantly different from its present configuration. Laskar (1994, 1996) already concluded that exoplanet systems with only one or two planets are improbable. If they do exist, they are likely to be crowded with the original planetesimals not ejected by planetary perturbations.

Multiple systems with large outer planets and small inner planets should be subject to instabilities similar to those evident in these simulations, including instabilities of obliquities along with the attendant varying 'climate' implications (Ward, 1973; Laskar & Robutel, 1993).

#### 12.4.5 Planet rotation

Planetary rotations arise from the accretion of angular momentum during their formation, and their spin rates soon after formation are believed to be much higher than their orbital mean motion (e.g. Agnor et al., 1999; Kokubo & Ida, 2007; Miguel & Brunini, 2010). In the solar system, observed equatorial rotation velocities (and spin angular momenta) generally increase with planet mass. Equatorial rotation velocities range from  $0.24 \text{ km s}^{-1}$  for Mars to  $13 \text{ km s}^{-1}$  for Jupiter, with resulting sidereal rotations of 1.03 d and 0.41 d respectively, albeit with some continuing uncertainties (e.g. Karkoschka, 2011). Exceptions to this trend are Mercury (Peale, 1988b) and Venus (Yoder, 1997) which have spun down since formation to  $\ll 0.1 \text{ km s}^{-1}$  because of tidal interactions with the Sun (Pettengill & Dyce, 1965; Correia & Laskar, 2001).

The Earth has also slowed, with tidal interaction with the Moon (Goldreich, 1966b; Neron de Surgy & Laskar, 1997; Čuk & Stewart, 2012; Deines & Williams, 2016) dominating more subtle effects such as growth of the Earth's core (Denis et al., 2011).

Figure 12.15 shows the pronounced log-linearity of angular momentum versus mass for those solar system planets largely unaffected by solar tides. The linearity extends over several more mass decades to include the asteroids (Fish, 1967; Hartmann & Larson, 1967; Burns,

1975). Most rotation periods are within a factor of three of the mean spin period of 10 h, whereas their masses range over fifteen orders of magnitude.

A historical review of the progress in knowledge of planetary spin periods is given by Hughes (2003).

**Models** Various attempts have been made to explain the mass–spin period correlation (e.g. Alfvén, 1964; Hartmann & Larson, 1967; Lissauer & Safronov, 1991; Lissauer & Kary, 1991; Kary & Lissauer, 1992; Dones & Tremaine, 1993a,b; Lissauer et al., 2000). For the terrestrial planets formed by the accretion of planetesimals orbiting the Sun in the same direction, the orbits being co-planar and nearly circular, the final planetary body might be expected to have an equatorial spin velocity that is some fraction of the escape velocity (Schlichting & Sari, 2007; Nayakshin, 2011c), with empirical evidence perhaps suggesting a value of 1/7 (Hughes, 2003).

**Ordered and stochastic accretion** Such arguments, supported by extensive orbital integrations, can be used to calculate the expected distributions of spin rate and obliquity as a function of the planetesimal mass and velocity distributions (e.g. Dones & Tremaine, 1993a,b; Miguel & Brunini, 2010). Depending on impactor mass, the planet’s final spin can either be due to many small bodies (*ordered accretion*), with the spin determined by the mean angular momentum of the impactors, or by a few large bodies (*stochastic accretion*), in which spin is a random variable whose distribution is determined by the rms angular momentum of the impactors.

For ordered accretion, the expected planet obliquity is near 0° or 180°, while there should be a wide range of obliquities if accretion is stochastic. The results of Dones & Tremaine (1993b) imply that the terrestrial planet spins are determined by stochastic accretion, with the more rapid spin rates of Earth and Mars attributed to one or more ‘giant’ impacts.

Such models are not applicable to the gas/ice giants, and in particular Jupiter or Saturn, which acquire most of their spin through hydrodynamical processes.

**Exoplanets** As of the end of 2017, four exoplanets have measured spin rates (Figure 12.15):  $\beta$  Pic b, PSO J318–22, and GQ Lup from radial velocities (§2.5.4), and 2M J1207 from photometric modulation with HST–WFC3 (§9.6.5).  $\beta$  Pic b ( $11 \pm 5M_J$ ) appears consistent with extrapolation of the solar system spin–mass trend, while the relatively slow rotation of GQ Lup is most likely due to its young age, < 5 Myr, and still accreting material and angular momentum (Schwarz et al., 2016a).

#### 12.4.6 Planet obliquities

The spins of the solar system planets are neither perfectly aligned nor randomly oriented. Their *obliquities*, the angle between their spin and orbital angular momentum vectors (Cox, 2000), range from 0°03 (Mercury),

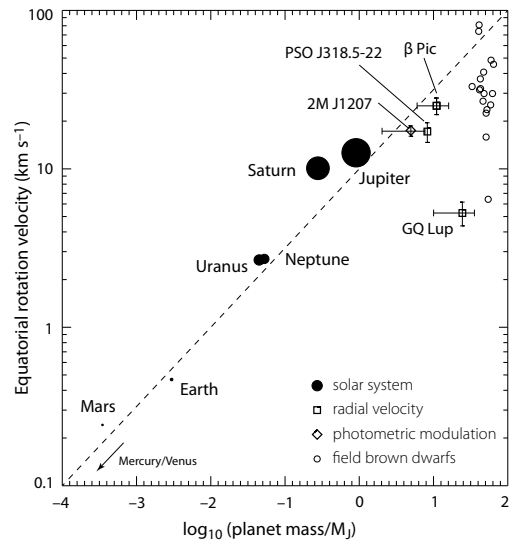


Figure 12.15: Equatorial rotation velocity for solar system planets as a function of  $M_p$ , with circle size proportional to  $R_p$ . Mercury and Venus are below the plot range, since tidal interactions with the Sun led to their spin down. The dashed line is purely indicative. The plot includes four exoplanets (not to scale) for which spin rates have been determined:  $\beta$  Pic b, PSO J318–22, and GQ Lup from radial velocity measurements, and 2M J1207 from photometric modulation. Open circles are projected spin velocities of field brown dwarfs from Schwarz et al. (2016a, their Figure 8). Adapted from Snellen et al. (2014, Figure 2a).

3°1 (Jupiter), 23°4 (Earth), 25°2 (Mars), 27° (Saturn), 30° (Neptune), 98° (Uranus), 118° (Pluto), and 177° (Venus). The solar obliquity is considered in Section 12.1.5.

The wide range of obliquities is demonstrably inconsistent with an isotropic distribution, with too many small values (Tremaine, 1991), and a degree of prograde rotation indicative of semi-collisional accretion (Schlichting & Sari, 2007). If the planets had grown smoothly and continuously by the accretion of small bodies and gas in an isolated flat disk, their obliquities should be zero. Accretion of a relatively small number of massive bodies, with a non-zero velocity dispersion normal to the disk, would impart the growing protoplanet with a randomly directed component of spin angular momentum (Kokubo & Ida, 2007), but would also lead to eccentricities and inclinations larger than observed (Harris & Ward, 1982). As a result, a combination of effects is likely responsible for the observed distribution.

**Mechanisms** Planetesimal or protoplanet collisions contribute to the observed obliquities, and imply stochastic rather than smooth accretion (Lissauer & Kary, 1991; Lissauer & Safronov, 1991; Dones & Tremaine, 1993b; Miguel & Brunini, 2010), as for Earth’s spin state (Dones & Tremaine, 1993a).

Excitation of a giant planet’s obliquity also arises if its spin axis precession passed through resonance with its orbital precession frequency during migration (Harris & Ward, 1982). For Uranus, tilt due to collision (Bergstrahl et al., 1991; Parisi, 2011) and during migration (Boué & Laskar, 2010) have both been

proposed, and similarly for Neptune (Parisi & Del Valle, 2011).

A Jupiter–Saturn resonance crossing during divergent migration, as in the Nice model (§12.6.3), has been proposed as an explanation of both the small obliquity of Jupiter and the large obliquity of Saturn (Mosqueira & Estrada, 2006; Brunini, 2006; Lee et al., 2007b; Vokrouhlický & Nesvorný, 2015). The origin of Saturn's obliquity has also been attributed to perturbations by Neptune (Ward & Hamilton, 2004; Hamilton & Ward, 2004). For Jupiter, a contribution from a resonance between the planetary orbit, and momentum loss from a variable protostellar jet with periodic polarity reversal, has also been suggested (Namouni, 2013; Veras et al., 2013a).

None of the terrestrial planet obliquities are believed to be primordial. Secular orbit perturbations are likely to have stimulated large and chaotic variations in the past. Tidal dissipation has since stabilised the obliquities of Mercury and Venus, while that of Mars, currently  $25^\circ$ , is still in a largely chaotic regime ranging from  $0$ – $60^\circ$  (Ward, 1973; Laskar & Robutel, 1993). Tidal dissipation has also driven the obliquities of the Galilean satellites of Jupiter to small but non-zero values (Bills, 2005).

Earth's obliquity (§12.3.3) may have been stabilised by the Moon (Laskar & Robutel, 1993; Laskar et al., 1993; Neron de Surgy & Laskar, 1997; Atobe & Ida, 2007). It may have received its present obliquity from the Moon-forming impact (Li & Batygin, 2014a), or a larger obliquity, of  $\sim 70^\circ$ , and a subsequent secular decrease due to core–mantle torques, with climatic consequences during the Proterozoic–Phanerozoic resulting from passages through critical values (Williams, 1993).<sup>8</sup>

Other contributions may arise from external torques, causing the total angular momentum of the planetary system to change after formation. This may be due to passing stars or molecular clouds (Heller, 1993), tidal interactions with other protostars (Larson, 1984; Wesson, 1984), orbiting satellites (Atobe & Ida, 2007), or a distant outer planet (Gomes et al., 2006), or the varying angular momentum of infalling material during protostellar collapse due to cloud inhomogeneities.

Effects due to climate feedback and volatile migration (cf. §11.3.8) have been considered in the case of the long-term axial tilt and present obliquity of Mars (Rubincam, 1990, 1993); the Earth (Bills, 1994); and for Triton and Pluto (Rubincam, 2003).

<sup>8</sup> At the present epoch, and as a consequence of N-body interactions, Earth's obliquity oscillates with an amplitude of  $2^\circ$ – $4^\circ$  ( $22^\circ$ – $24^\circ$ ) over a period of  $\sim 41$  000 yr. The collective effects on the Earth's climate of long-term variations in this axial tilt, along with changes in orbital eccentricity and precession, are usually referred to as *Milankovitch cycles*, after the contributions of Milankovitch (1941) [in English translation, Milankovitch 1969]. In the absence of secular changes in the semi-major axis  $a$ , orbital effects on the Earth's climate are described by two independent parameters, the obliquity  $\epsilon$ , and the *climatic precession index*,  $\Delta e \sin \bar{\omega}$  (where  $e$  is the eccentricity, and  $\bar{\omega}$  is the longitude of perihelion). Although any dependency was largely discarded in the 1960s, geological data from deep ocean cores led to the theory's revival in the 1970s. Imbrie (1982) reviews the development of the astronomical theory of the Pleistocene ice ages, the role of the Earth's orbit, and the key publications in astronomy, climatology, and geology, pre-1982 (e.g. Berger, 1976, 1977a,b, 1980; Hays et al., 1976; Weertman, 1976; Schneider, 1979; Imbrie & Imbrie, 1980; Ghil & Le Treut, 1981; Kutzbach, 1981). For an introduction to the additional effects of variations in solar irradiance, see, e.g. Keller (2004). Studies continue to be reported (e.g. Markonis & Koutsoyiannis, 2013).

## 12.5 Minor bodies in the solar system

The minor bodies of the solar system include remnants of its primordial formation, along with components of its own highly-evolved debris disk (box, page 452). Considerations of other disk systems (§10.6) alongside that of the solar system have contributed to an improved understanding of both (Matthews & Kavelaars, 2016).

Solar system objects can be classified in terms of their orbit, but also by their mass, composition, and solid state characteristics including their shape (Remo, 2007). The resulting categorisations according to heliocentric distance, or to orbit, size, morphology, and composition, are consequently frequently overlapping.

Modern discussions also refer to 'planetesimals' and 'planet embryos', which appear in the current concepts of planet formation (Chapter 10). In this paradigm, the early solar system solids, initially dust particles, coagulated to form planetesimals. Starting in a dynamically-cold disk (i.e. with small eccentricities and inclinations), the collisional evolution of these planetesimals led to the formation of a limited number of more massive bodies referred to as planetary embryos, by the processes of runaway and oligarchic growth. The embryos collided further, leading to the assembly of the terrestrial planets (along with giant impacts like that postulated for the origin of the Moon). Further out, more massive cores acted as the centres for runaway gas accretion and to the formation of the giant planets.

**Space missions to asteroids and comets** Comets have been observed by numerous fly-by missions, including Giotto to Halley (fly-by in 1986, then redirected to a 200 km fly-by of Grigg–Skjellerup in 1992), and the sample return Stardust to Wild 2 (fly-by in 2004, then redirected to Tempel 1). There have been 'visits' by two probes: ESA's Rosetta, launched in 2004, with Philae landing on 67P/Churyumov–Gerasimenko in 2014, and NASA's Deep Impact, which released an impactor into Tempel 1 in 2005 (subsequently designated EPOXI). On their journeys, Stardust made a 3000-km fly-by of asteroid 5535 Annefrank in 2002 (Hillier et al., 2011), and Rosetta made a 3000-km fly-by of asteroid 21 Lutetia in 2010 (Sierks et al., 2011).

NASA's Dawn mission, launched in 2007, targeted orbiting two of the three protoplanets of the asteroid belt, Vesta and Ceres. It orbited Vesta for 14 months in 2011–12 (e.g. Marchi et al., 2014), and entered its long-term Ceres orbit in 2015. Amongst the objectives, detailed cratering records provide constraints on aspects such as their formation, on the initial configuration of the giant planets, and on the epoch of the Late Heavy Bombardment (de Elia & di Sisto, 2011; Turrini et al., 2011).

After its fly-by of Pluto, New Horizons is scheduled to pass the Kuiper belt object 2014 MU<sub>69</sub> in January 2019.

JAXA's asteroid sample return mission Hayabusa-2, and its lander MASCOT, was launched in 2014 December. It targets asteroid 162173 Ryugu, with expected arrival in 2018 July. NASA's OSIRIS-REx is an asteroid sample return mission, launched in 2016, aiming to rendezvous with the 500-m diameter near-Earth asteroid 101955 Bennu on 2020 July 4 (Müller et al., 2012; Lauretta et al., 2015; Lauretta & Clark, 2016).

### 12.5.1 Dwarf planets

According to the IAU 2006 definition (§1.5), a *dwarf planet* is an object in direct orbit around the Sun, massive enough for self-gravity to impose a hydrostatic equilibrium shape, but which has not cleared its neighbourhood of other orbiting material. The definition was prompted by the discovery of trans-Neptunian objects of similar size to Pluto, including the more massive Eris.

The classification, and agreeing on which objects are ‘true members’, remains problematic, in part due to the limited information available on candidate objects. The term, introduced by Stern (1991), was originally used to classify objects with diameters above 1000 km. He argued that the large obliquities of Uranus and Neptune, the capture of Triton, and the formation of the Pluto–Charon binary, imply the presence of numerous such bodies at around 20–50 au.

The IAU currently recognises five dwarf planets: Ceres, Pluto, Haumea, Makemake, and Eris, although only Ceres and Pluto have been observed in enough detail to demonstrate that they robustly meet the IAU definition. Many more are candidates: a recent online compilation (dwarf planets, Table 1.4) lists 10 known objects as ‘nearly certain’, 30 as ‘highly likely’, and several hundred as ‘likely’ or ‘possible’. Some 200 may lie within the Kuiper belt, and possibly more than 10 000 including objects scattered beyond.

All four of the currently-designated trans-Neptunian dwarf planets host one or more satellites, allowing determination of their mass and density, the last of the four discovered being that of Makemake (Parker et al., 2016).

**Pluto** Pluto, discovered by Tombaugh in 1930, was originally considered to be the ninth planet from the Sun. With the definition of a planet as formalised by the IAU, Pluto was re-classified as a dwarf planet, and accordingly the first Kuiper belt object to be discovered. It remains the largest known dwarf planet, and the second most massive ( $M \sim 0.18M_{\text{Moon}}$ ) after Eris. It has a moderately eccentric orbit ( $e = 0.25$ ,  $a = 39.5$  au,  $P = 248$  yr), inclined to the ecliptic by  $17^\circ$ .

With a heliocentric distance 30–49 au, Pluto periodically comes closer to the Sun than Neptune, although always with  $\Delta > 17$  au due to their 2:3 mean motion resonance (Malhotra, 1993a). Pluto’s orbit is chaotic, with a Lyapunov time of 10–20 Myr (Sussman & Wisdom, 1988).

Pluto has five known moons: the innermost and largest, Charon, was discovered in 1978 (Christy & Harrington, 1980). Nix and Hydra were discovered by HST in 2005 (Weaver et al., 2006), and Kerberos and Styx in 2011–12 (Showalter et al., 2012). The Pluto–Charon system is considered to have formed by collision (Canup, 2005; Stern et al., 2006), with the smaller satellites probably formed from the debris disk or impact debris growth (Canup, 2011; Youdin et al., 2012; Kenyon & Bromley, 2014b; Walsh & Levison, 2015; Michaely et al., 2017).

**Designation of solar system minor bodies:** Object designation by the IAU Minor Planet Center, e.g. 2012 VP<sub>113</sub>, encodes the discovery date. It comprises the year; a letter to show the ‘half-month’; a second letter to show the order within the half-month; and a number indicating the number of times the second letter has been repeated in that half-month (see [www.minorplanetcenter.net](http://www.minorplanetcenter.net)). *Unnamed* minor planets are often preceded by their MPC number in parenthesis, thus (388188) 2006 DP<sub>14</sub>, while MPC numbers of *named* minor planets may appear with or without parenthesis, e.g. 10969 Perryman.

New Horizons, launched in 2006, was the first to fly by Pluto, on 2015 July 14, making detailed measurements of Pluto and its moons (e.g. Stern, 2008; Stern et al., 2015; Nimmo et al., 2017).

From HST, New Horizons, infrared, occultation, and other observations, many details are known about Pluto’s surface composition, as well as its tenuous atmosphere. Like other Kuiper belt objects, Pluto is primarily made of ice and rock, with the surface plains composed of more than 98% N<sub>2</sub> ice, with traces of CH<sub>4</sub> and CO (e.g. Owen et al., 1993; Young, 2013; Grundy et al., 2013; Merlin, 2015; Grundy et al., 2016; Sicardy et al., 2016).

### 12.5.2 Planetesimals and protoplanets

Planetesimals which grew to modest size without forming larger objects, as well as post-collisional debris, are represented by asteroids, comets, and meteoroids.

*Asteroids:* these are small solar system bodies which are generally held to have formed inside Jupiter’s orbit rather than in the outer solar system, composed primarily of minerals or rock, i.e. a combination of iron- and magnesium-bearing silicates and metallic iron (§12.5.4). A contribution to the asteroid belt from populations formed at larger radial distances is suggested by current migration models (§12.6.4).

*Comets:* these are small solar system bodies that formed further out in the solar system, composed primarily of ices and dust (§12.5.7).

*Meteoroids:* amongst the various (and frequently loose) definitions of these different terms (e.g. Beech & Steel, 1995), Rubin & Grossman (2010) define a *meteoroid* as a 10  $\mu\text{m}$ –1 m-size natural solid object moving in interplanetary space, and a *micrometeoroid* as a meteoroid 10  $\mu\text{m}$ –2 mm in size. Most are fragments from comets or asteroids, while others are collisional debris, either ejected from bodies such as the Moon or Mars, or impact debris from the final stage of the solar system formation, extending to the interplanetary dust found by Pioneer beyond Saturn (Landgraf et al., 2002).

*Meteorites* are generally taken to be fragments of (proto)planetary material that have survived their passage through the atmosphere to land on Earth (box, page 683). More generally, Rubin & Grossman (2010) define a *meteorite* as a natural solid object larger than

**Meteorites:** *Meteorites* are fragments of (proto)planetary material that have survived their passage through the atmosphere to land on Earth. All known meteorites are fragments of either asteroids, the Moon, or Mars, with the former dominating. They display a large diversity of texture and mineralogy. Most are ancient, dating from the first 10 Myr of the solar system formation. Some  $10^5 - 10^6$  kg of meteoritic material falls on Earth each day.

Modern meteorite taxonomy is complex (Weisberg et al., 2006; Krot et al., 2007). Some 86% are *chondrites*, which retain some record of geochemical process in the solar neighbourhood. Some 8% are *achondrites*, which underwent subsequent melting and differentiation. Around 5% are Fe meteorites which, from their cooling rates of  $1-10 \text{ K Myr}^{-1}$  (inferred from the Thomson–Widmånstatten structures of Ni-rich taenite and Ni-poor kamacite), are considered to have originated from the cores of once-molten asteroids. The remaining 1% are the stony-iron meteorites, a mixture of Fe–Ni metal and silicate minerals.

Chondrites were originally defined as meteorites containing chondrules; now the term signifies a bulk chemical composition, excluding the most volatile elements, similar to that of the Sun. *Carbonaceous chondrites* are those with bulk refractory lithophile abundances, normalised to Si, equal to or greater than that of the solar photosphere. They generally contain carbon compounds, water (as OH within silicate minerals), and other volatiles although, despite the name, they can be relatively poor in carbon.

Chondritic meteorites comprise *chondrules*, spherical bodies that existed prior to their incorporation into meteorites and which show evidence for partial or complete melting (e.g. Elkins-Tanton et al., 2011); *calcium-aluminium-rich inclusions (CAIs)* composed largely of Ca, Al, and Ti oxides; and a matrix of varying composition and origin, including presolar grains, nebular condensates, and CAI and chondrule fragments.

Meteorites trace key stages in the solar system evolution, viz. the initial interstellar medium, protostellar collapse, disk formation, dust condensation and coagulation, thermal processing, and planetesimal and planet formation. Isotopic anomalies and oxidation states provide constraints on formation models (Apai & Lauretta, 2010).

$10 \mu\text{m}$ , derived from a celestial body, that was transported by natural means from the body on which it formed to a region outside the dominant gravitational influence of that body and that later collided with a natural or artificial body larger than itself. A *micrometeorite* is a meteorite between  $10 \mu\text{m}-2 \text{ mm}$  in size.

**Protoplanets** Examples of protoplanets which have survived more-or-less intact are (dwarf planet) Ceres and asteroids Pallas and Vesta in the inner solar system, and perhaps the Kuiper belt dwarf planets further out.

### 12.5.3 Exchange of impact ejecta

In the solar system, there is known to be an exchange of impact ejecta among the terrestrial planets, and similar processes presumably occur in extrasolar environments.

**Martian meteorites on Earth** The Meteoritical Bulletin Database (Table 1.4; Ruzicka et al., 2015) lists over 61 000 meteorites that have been found on Earth, of which 132 are Martian. These are *achondritic* (stony), divided into shergottites, nakhlites, and chassignites, and accordingly known as the *SNC group* (Smith et al., 1984).

SNC meteorites are thought to be from Mars because of their elemental and isotopic similarity to rocks and atmospheric gases analysed by the Viking landers (Treiman et al., 2000), and by the Mars Curiosity Rover (Atreya et al., 2013). More specifically, they have younger formation ages, a different oxygen isotopic composition, the presence of aqueous weathering products, and some compositional similarity to Martian surface rocks.

Gladman et al. (1996) modeled the exchange process by numerically integrating the orbital histories of ejecta from the terrestrial planets to study their transfer to Earth. They found that the properties of lunar and Martian meteorites are consistent with a recurrent ejection of small meteoroids as a result of impacts on their parent bodies. Long-range gravitational effects, especially secular resonances, strongly influence their orbits, increasing their collision rates with other planets and the Sun. These effects, along with collisional destruction in the asteroid belt, result in shortened time scales and higher fluxes than previously believed, especially for Martian meteorites. They also found that a small flux of Mercury ejecta appears possible, while recovery of meteorites from the Earth and Venus is less likely.

**Particles from beyond the solar system** Particles larger than  $\sim 10 \mu\text{m}$  may propagate for tens of pc through the interstellar medium, and have probably been detected by ground-based radar (Arecibo/New Zealand), and by satellites (Murray et al., 2004; Musci et al., 2012; Hajdukova, 2016). Macroscopic bodies passing through the solar system are considered in Section 12.5.14.

### 12.5.4 Asteroids

Asteroids are a subset of small solar system bodies, along with comets and meteoroids, which never grew large enough to become planets. While comets are composed of ices and dust, reflecting their formation further from the Sun, asteroids are mainly composed of rocks and minerals. The difference between asteroids and meteoroids is mainly one of size, the boundary between them arbitrarily considered as 1 m (Rubin & Grossman, 2010), with asteroids extending to some 1 km or more in size.

Individual asteroids are classified by their spectra, with the majority falling into three main groups: C-type (carbon-rich), M-type (metallic), and S-type (silicate or stony). The present size frequency distribution of bodies in the asteroid belt appears to have preserved some record of the primordial population, with an excess of bodies of diameter 100 km relative to a simple power law (Weidenschilling, 2011).

There are more than  $10^6$  known asteroids, some 750 000 having orbits sufficient to be assigned designations by the IAU. The majority orbit in the asteroid belt between Mars and Jupiter, some with high inclinations (e.g. Novaković et al., 2011), or even retrograde orbits (§12.5.9). Other classes include the 1:1 resonant Trojans (§12.5.11), and the near-Earth objects (box, page 688).

The co-existence of main belt asteroids with different physical properties may be explicable in terms of the Grand Tack model (§12.6.4). Similarly, their size distribution reflects both their primordial formation and their subsequent collisional evolution, including a possible ‘Jovian Early Bombardment’ (Turrini et al., 2012).

**Vesta** After the dwarf planet Ceres, Vesta is the second largest ( $R = 260$  km) and second most massive body in the asteroid belt. Observations, including with Dawn, lead to its classification as a rocky differentiated protoplanet, i.e. of the kind that formed the terrestrial planets, with a metallic Fe core ( $R = 110$  km) and basaltic crust. Significant cratering from collisions some 1–2 Ga, resulted in the family of HED (howardite–eucrite–diogenite) meteorites, a rich source of information about the parent body (e.g. De Sanctis et al., 2013).

**Comet-like outbursts** Outbursts attributed to impact events are occasionally observed. Comet-like comae which have developed around asteroids, and attributed to collisions in the main asteroid belt include 596 Scheila (Larson, 2010; Moreno et al., 2011; Granata et al., 2011), and 3552 Don Quixote (Mommert et al., 2014).

**Centaurs** Centaurs are small bodies between Jupiter and Neptune, with unstable orbits that cross those of the giant planets, resulting in dynamical lifetimes of typically 5–50 Myr. They are assumed to originate either as scattered disk objects which interact with Neptune (e.g. Horner et al., 2004a; Volk & Malhotra, 2013), or from the Oort cloud (Brasser et al., 2012b). Centaurs typically behave with characteristics of both asteroids and comets, representing a link between the short-period Jupiter-family comets and the reservoir of icy bodies in the outer solar system (Levison & Duncan, 1997).

**Shape** Disruptive collisions among asteroids generate fragments with mean axis ratios  $2 : \sqrt{2} : 1$  (e.g. Ryan, 2000a; Szabó & Kiss, 2008; Domokos et al., 2015). The outcome of non-disruptive impacts is mainly determined by the fragment/impactor mass ratio,  $M/m$ . Large to moderate  $m \geq M$  leads to curvature-driven abrasion which tends to make objects rounder, while low-energy impact collisions with high speed impactors of mass  $m \ll M$  makes the asteroid less spherical through polyhedral abrasion (Domokos et al., 2009). Models and outcomes may be partially informed by weathering processes which shape rocks and pebbles on Earth (e.g. Åström et al., 2004; Durian et al., 2006; Krapivsky & Redner, 2007; Domokos et al., 2014).

### 12.5.5 Trans-Neptunian objects

Within the orbit of Neptune, *cis-Neptunian bodies* include the terrestrial and large gaseous planets, along with a variety of minor bodies: planetary moons, asteroids, and comets. Orbiting the Sun at a greater mean distance than Neptune,  $a > 30$  au, *trans-Neptunian objects* (TNOs) are remnants of a collisionally- and dynamically-evolved planetesimal disk in the outer solar system (Schulz, 2002). They can be further sub-divided spatially, and somewhat subjectively, into various classes, including the Kuiper belt (§12.5.6) and the Oort cloud (§12.5.7). They often exhibit large eccentricities and high inclinations, which can also be grouped into distinct dynamical classes (§12.5.6).

The first discovered was Pluto in 1930, followed by 1992 QB<sub>1</sub>. The largest known, and all also classified as dwarf planets (§12.5.1), are sequentially Pluto, Eris (the most massive), 2007 OR<sub>10</sub>, Makemake and Haumea.

Recent or ongoing surveys include the Deep Ecliptic Survey (DES; Elliot et al., 2005; Adams et al., 2014); the Canada–France Ecliptic Plane Survey (CFEPS; Gladman et al., 2012); and the (CFHT) Outer Solar System Origins Survey (OSSOS; Bannister et al., 2016).

At the end of 2017, there are 1900 TNOs on the Minor Planet Center’s list (Table 1.4), some 300 having well-determined orbits meriting a minor planet designation.

**Binary TNOs** Trans-Neptunian objects include numerous binaries (as do the interior Centaurs), including Pluto–Charon, and the second binary discovery 1998 WW<sub>31</sub>. Such binaries provide constraints on the solar system formation, including subsequent planetary migration (e.g. Lee et al., 2007a; Noll et al., 2008; Parker & Kavelaars, 2010; Kominami et al., 2011; Murray-Clay & Schlichting, 2011; Parker et al., 2011; Parker & Kavelaars, 2012; Porter & Grundy, 2012; Compère et al., 2013; Kominami & Makino, 2014). Spin–orbit, spin–spin, and spin–orbit–spin resonances may result (Hou & Xin, 2017).

**Extreme TNOs** Some dozen objects with  $a > 150$  au and  $q > 30$  au, termed *extreme trans-Neptunian objects*, are also known (de la Fuente Marcos & de la Fuente Marcos, 2014). Suggestive of perturbation by some external force, various origins have been conjectured, including evidence for a super-Earth (Planet Nine) in the outer solar system, binary stripping, and MOND dynamics (e.g. de la Fuente Marcos et al., 2015; Sheppard & Trujillo, 2016; Paučo, 2017; de la Fuente Marcos et al., 2017; de la Fuente Marcos & de la Fuente Marcos, 2017a).

### 12.5.6 The Kuiper belt

The *Kuiper belt*, or *Edgeworth–Kuiper belt*, is a subset of all trans-Neptunian objects, and taken as extending from the orbit of Neptune (30 au) to approximately 50 au. As part of the solar system’s circumstellar disk, it includes remnants of the Sun’s protoplanetary disk (Jewitt & Luu, 1993; Williams, 1997; Jewitt, 1999; Chiang et al., 2007). It is similar to the asteroid belt, but some 20 times wider, and some 20–200 times as massive.



Like the asteroid belt, it consists mainly of small bodies. However, in contrast to the asteroidal composition of primarily rock and metal, most Kuiper belt objects are composed largely of frozen volatiles, such as  $\text{CH}_4$ ,  $\text{NH}_3$ , and  $\text{H}_2\text{O}$ .

The Kuiper belt is believed to include objects that originally formed within the giant planet region, along with objects that formed beyond them (Gomes, 2003; Levison & Morbidelli, 2003; Levison et al., 2008; Walsh et al., 2011). Their diverse surface colours (Luu & Jewitt, 1996; Fraser & Brown, 2012) are attributed to a combination of their original formation location within the solar nebula, along with subsequent environmental changes due to space weathering, cratering, and fragmentation Sheppard (2012). Progress in object characterisation (including sizes, albedos, and densities) is being made through various ground and space-based facilities, including Herschel and Spitzer (e.g. Mommert et al., 2012; Vilenius et al., 2012, 2014; Duffard et al., 2014).

Of the five ‘recognised’ dwarf planets (§12.5.1), the Kuiper belt hosts three: Pluto, Haumea, and Makemake. Moons including Neptune’s Triton (Agnor & Hamilton, 2006) and Saturn’s Phoebe (Johnson & Lunine, 2005), are also thought to have originated in the region.

The size distribution of Kuiper belt objects provides empirical constraints on models of growth during planet formation more generally (e.g. Kenyon, 2002; Schlichting & Sari, 2011; Kenyon & Bromley, 2012; Brown, 2013; Schlichting et al., 2013; Shannon et al., 2016b). As for the TNOs more generally, other constraints on formation are provided by the incidence of prograde and retrograde binary orbits (e.g. Schlichting & Sari, 2008).

**Dynamical populations** The orbits of the Kuiper belt (and other trans-Neptunian) objects preserves information about the past evolution of the solar system and its planetesimal disk (§12.6), with most (but not all) left in low-inclination orbits (Levison & Morbidelli, 2003; Lykawka & Mukai, 2007; Levison et al., 2008).

Kuiper belt objects (KBOs) are classified in several distinct dynamical groupings, with different colours reflecting their differing origins (e.g. Sheppard, 2012):

*Classical Kuiper belt objects*, with  $42 \lesssim a \lesssim 48$  au and low-to-moderate  $e$ , further divided into *cold classical KBOs* ( $i < 5 - 10^\circ$ ), and higher inclination *hot classical KBOs* (Brown, 2001a; Dawson & Murray-Clay, 2012);

*Scattered disk objects*, with pericentre near Neptune ( $q \sim 25 - 35$  au), large eccentricities ( $e > 0.4$ ), and often large inclinations up to  $i \sim 40^\circ$ . The scattered disk was likely created through strong dynamical interactions with Neptune (Duncan & Levison, 1997; Gomes et al., 2005a; Duncan, 2008; Gomes et al., 2008). *Detached disk objects* have similar eccentricities ( $e > 0.25$ ) but higher  $q$  ( $q \gtrsim 40$  au), are unlikely to have been scattered by Neptune in the current solar system configuration, and may represent fossilised disk objects scattered

during Neptune’s outward migration (Gladman et al., 2002; Lykawka & Mukai, 2006, 2008; Gomes, 2011);

*Resonant Kuiper belt objects*, in mean motion resonance with Neptune (Elliot et al., 2005; Lykawka & Mukai, 2007; Gladman et al., 2008), and likely captured during Neptune’s outward migration (Malhotra, 1995; Chiang & Jordan, 2002; Chiang et al., 2003; Hahn & Malhotra, 2005; Murray-Clay & Chiang, 2005; Levison et al., 2008). Resonant populations include the Neptune Trojans (1:1; §12.5.11), and those with semi-major axes interior to (5:4, 4:3, 3:2), within (5:3, 7:4), and exterior to (2:1, 7:3, 5:2, 3:1) the classical Kuiper belt. The 3:2 resonance objects are known as *Plutinos* (after the prototype Pluto), and the 2:1 resonance objects as *Twotinos*. The first example of an object with a nearly polar orbit in resonance with a planet is the trans-Neptunian object ‘Niku’, in a 7:9 resonance with Neptune, and with a mean lifetime in resonance of 16 Myr (Morais & Namouni, 2017).

**Kuiper belt dust disk** The Kuiper belt hosts an associated dust disk, one component of the solar system’s zodiacal dust cloud (§12.5.13), generated from planet–dust interactions and grain–grain collisions as in other debris disks. In contrast to other debris disks, where dust can be seen as an infrared excess over the stellar photosphere, detection of the Kuiper belt dust is hampered by foreground zodiacal emission. Various 3d structure models have been constructed, including effects due to trapping and clearing by Neptune and Saturn (e.g. Booth et al., 2009; Kuchner & Stark, 2010; Vitense et al., 2012, 2014; Klačka & Kocifaj, 2015; Poppe, 2016).

### 12.5.7 Comets

Comets are small icy bodies that are believed to have formed beyond the snow line. Sometimes described as ‘dirty snowballs’, they comprise frozen ice ( $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ), dust grains, and small rocky particles, and range from a few hundred meters to tens of km in size (Hahn & Malhotra, 1999). Those observed in the inner solar system usually have highly eccentric orbits, and orbital periods ranging from several years to possibly several Myr. When passing close to the Sun, they sublimate and become active, producing a visible atmosphere or coma (due to solar radiation), and sometimes also a tail (due to the particulate solar wind). More than 5000 are known.

Comets have three known reservoirs (Dones et al., 2015): the roughly spherical Oort cloud ( $T_{\text{eq}} \sim 10$  K), the flattened Kuiper belt ( $T_{\text{eq}} \sim 40$  K) and, as recognised only recently, the *main belt comets*, having stable orbits confined to the main asteroid belt (Hsieh & Jewitt, 2006).

A small number of main belt comets are now known. Originally considered to have formed where they now reside (but see §12.6.4), and possibly collisionally activated (e.g. P/2010 A2 LINEAR, Hainaut et al. 2012; 3552 Don Quixote, Mommert et al. 2014), the existence of

main belt comets lends new support to the idea that main belt objects could be a source of terrestrial H<sub>2</sub>O (§12.3.4). The discovery of main-belt comets and active Centaur minor planets has further blurred the distinction between asteroids and comets, with Chiron and Echeclus classified as both asteroids and comets.

Based on their orbital characteristics, short-period comets ( $P \lesssim 200$  yr) are thought to originate mainly from the Kuiper belt and scattered disk, with long-period comets thought to originate from the more distant spherical Oort cloud, set in motion towards the Sun by gravitational perturbations caused by the Galactic tidal field or passing stars (e.g. Collins & Sari, 2010).

**Oort cloud** The *Oort cloud* is a hypothesised assembly of some  $10^{12}$  predominantly icy planetesimals surrounding the Sun, of typical size 1 km, and with a total mass of a few  $M_{\oplus}$ . Although no direct observations of the Oort cloud have been made, its existence is inferred from the fact that, given the instability of cometary orbits and their loss of volatiles when heated during perihelion passage, a continuous replenishment source must be present.

It is inferred to comprise a spherical *outer Oort cloud* (Öpik, 1932; Oort, 1950), and a disk-shaped *inner Oort cloud* (Hills, 1981; Levison et al., 2001b). Extending out to 50–200 kau ( $\sim 1$  au) or more (Hills, 1981), far beyond the Kuiper belt to the boundary of the Sun's Hill sphere (e.g. Smoluchowski & Torbett, 1984), it demarcates the outer limits of the solar system<sup>9</sup>. Its innermost extension is perhaps represented by Sedna (§12.5.8).

It is conjectured that the constituent bodies formed closer to the Sun, and were gravitationally scattered outward by the giant planets early in the solar system's evolution (e.g. Duncan et al., 1987; Brasser et al., 2006, 2012a; Dones et al., 2015). Some 4% may have been born within 2.5 au of the Sun, and hence of a primarily rocky or iron composition (Shannon et al., 2015a). Expelled at close to the solar system escape velocity, some would have been perturbed into long-lived orbits by nearby stars or the Galactic tidal field. Conversely today, gravitational forces of passing stars and the Galactic tidal field dislodge the icy planetesimals from their orbits within the Oort cloud, and send them towards the inner solar system (e.g. Heisler & Tremaine, 1986; Matese & Whitman, 1989; Emel'yanenko et al., 2007).

Compositionally, if comet analyses are representative, the majority of Oort cloud objects are inferred to consist of ices such as H<sub>2</sub>O, CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, CO, and HCN (e.g. Gibb et al., 2003). Observationally, comets are generally distinguished from asteroids by the presence of

an extended, gravitationally unbound atmosphere surrounding their central nucleus. However, comets that have passed close to the Sun many times may have lost much of their volatile ices and dust, and may come to resemble small asteroids.

It is plausible that the Sun captured comets from other stars early in its history, implying that some Oort cloud comets may be from the protoplanetary disks of other stars (Levison et al., 2010). Hanse et al. (2018) found that exocomets in analogous systems are transferred to the Oort cloud only during (very rare) relatively slow ( $< 0.5$  km s<sup>-1</sup>) and close ( $\lesssim 10^5$  au) encounters. Over the past 4 Gyr, the Oort cloud would have lost 25–65% of its mass, mainly due to stellar encounters, and at most 10% of its mass can be captured, although exocomets are often lost shortly after the encounter, with the resulting fraction of exocomets in the Oort cloud being about  $10^{-5} - 10^{-4}$ .

**Comet cloud of  $\alpha$  Cen** The comet cloud of the  $\alpha$  Cen system has been explicitly considered (e.g. Hills, 1981; Beech, 2011). Extending to  $\sim 1.3$ – $1.7$  pc (Kervella et al., 2017; Mamajek, 2017), similar to its distance of 1.3 pc, the solar system may also be on the outskirts of the  $\alpha$  Cen cometary cloud.

### 12.5.8 Sedna, Planet X and Planet Nine

The minor planet (90377) Sedna (2003 VB<sub>12</sub>) is a large ( $D \sim 1000$  km) object in the outer solar system, whose large orbit inclination and eccentricity ( $a = 506$  au,  $i \sim 12^\circ$ ,  $e = 0.85$ ,  $P = 11400$  yr,  $q = 76$  au,  $Q = 936$  au) present a challenge in understanding its origin (Brown et al., 2004; Kenyon & Bromley, 2004b; Kaib et al., 2011c; Jilková et al., 2015). It will reach pericentre in 2075–76.

2012 VP<sub>113</sub> ( $D \sim 500$  km,  $e > 0.7$ ,  $q > 30$  au) is a subsequent discovery in a similar orbit (Trujillo & Sheppard, 2014), thus confirming that Sedna is not an isolated case. Both may be members of a highly-populated inner Oort cloud, and links between the Kuiper belt objects and the hypothesised outer Oort cloud (Figure 12.16).

The observed distribution of the arguments of pericentre for Sedna, 2012 VP<sub>113</sub>, and other extreme trans-Neptunian objects unperturbed by Neptune was found to be concentrated around  $\omega \sim 0^\circ$  (Trujillo & Sheppard, 2014; de la Fuente Marcos & de la Fuente Marcos, 2014). The most distant also exhibit a clustering in their longitudes of ascending node,  $\Omega$  (Batygin & Brown, 2016a).

**Planet Nine** One explanation for this unexpected distribution in  $\omega$  invokes the existence of a (super-Earth) planet with  $M \sim 2 - 15M_{\oplus}$  and  $a \sim 200 - 300$  au (Trujillo & Sheppard, 2014). The hypothesised object is referred to as *Planet Nine*, also recalling earlier debates as to the existence of a Planet X (e.g. Lowell, 1915; Seidelmann & Harrington, 1988; Gomes, 1989; Standish, 1993).

<sup>9</sup>Some indication of scale is given by the fact that Voyager 1, the fastest and most distant space probe, will only reach the Oort cloud in  $\sim 300$  yr, and will take 30 000 yr to pass through it, passing neighbouring planetesimals spaced by tens of Mkm.

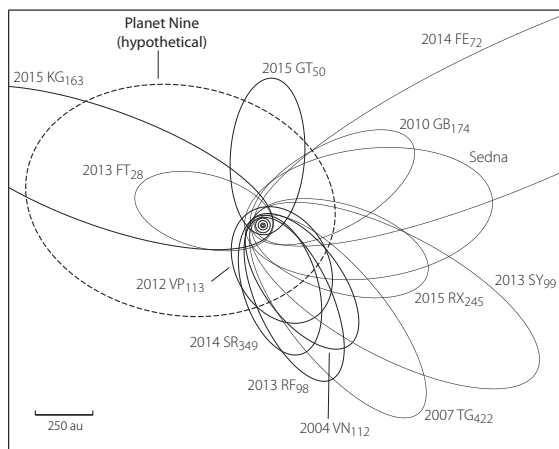


Figure 12.16: Orbit of the hypothetical Planet Nine, with 13 extreme trans-Neptunian object with orbits comparable to that of Sedna. Orbital parameters from the Minor Planet Center. This version was kindly prepared by Tom Ruen.

In this scenario, a population of stable asteroids is shepherded by the (undetected) Planet Nine, which maintains their argument of pericentre librating around  $0^\circ$ , and removes other bodies that were originally more uniformly distributed (de la Fuente Marcos & de la Fuente Marcos, 2014). Inferred properties are  $M \sim 10M_\oplus$ ,  $a \sim 650 - 700$  au and  $e \sim 0.5 - 0.6$  (Batygin & Brown, 2016a; Medvedev et al., 2017; Millholland & Laughlin, 2017a), with a magnitude (depending on albedo, radius, and distance) of  $V = 20 - 23$  (Linder & Mordasini, 2016).

**Searches and origin of Planet Nine** Various searches and constraints, including from Cassini, have been reported (Matese & Whitmire, 2011; Iorio, 2012a, 2014; Batygin & Brown, 2016a,b; Beust, 2016; Brown & Batygin, 2016; de la Fuente Marcos & de la Fuente Marcos, 2016a; de la Fuente Marcos et al., 2016; de la Fuente Marcos & de la Fuente Marcos, 2016b; Fienga et al., 2016; Fortney et al., 2016a; Holman & Payne, 2016a,b; Linder & Mordasini, 2016; Malhotra et al., 2016; Sheppard & Trujillo, 2016; Toth, 2016; Batygin & Morbidelli, 2017; Meisner et al., 2017; Iorio, 2017; Eriksson et al., 2018). Particularly supportive is the discovery of 2013 FT28, anti-aligned in perihelion longitude (Sheppard & Trujillo, 2016). Its mass and radius could be derived from occultations, or from microlensing (Philippov & Chobanu, 2016; Schneider, 2017).

One plausible formation scenario provides some support for ‘pebble accretion’ (§10.4.4) having occurred in the solar system (Kenyon & Bromley, 2016a; Levi et al., 2017a). Other studies have assessed: orbit generation and survival prospects (Li & Adams, 2016; Veras, 2016b), its (improbable) capture from other stars in the Sun’s birth cluster (Li & Adams, 2016; Mustill et al., 2016; Parker et al., 2017); cooling times and infrared detection (Ginzburg et al., 2016a; Mallama et al., 2017); and the possibility that it is a dark matter object (Sivaram et al., 2016).

The existence of such an object would affect the mass distribution of material beyond 50 au, as well as the spatial distribution and dynamical stability of objects between 40–50 au (Lykawka & Mukai, 2008; Kenyon & Bromley, 2015b; Becker et al., 2017a). The mass distribution in the outer parts of the solar system provides constraints on its formation, and on the

mass and outer radius of the solar nebula (Bromley & Kenyon, 2014). A low eccentricity orbit would be compatible with migration (Ward, 1997a; Crida et al., 2009b), while higher eccentricities for low-mass planets would be more compatible with gas-drag formation (Kenyon & Bromley, 2015b). It may have been gravitationally scattered outward by Jupiter or Saturn (Bromley & Kenyon, 2016). Such an object has also been invoked to explain periodicities in mass extinctions (Raup & Sepkoski, 1984; Whitmire, 2016). It may also offer an explanation for the observed solar obliquity (§12.1.5).

**Mass in the outer solar system** Other constraints on outer solar system objects may be obtained from: infrared imaging (e.g. Luhman, 2014a), pulsar timing (e.g. Zakamska & Tremaine, 2005; Champion et al., 2010); dynamics of the inner solar system (Iorio, 2009); and via astrometric microlensing (§5.8), perhaps from Gaia (Gaudi & Bloom, 2005; Philippov & Chobanu, 2016).

### 12.5.9 Retrograde orbits

Some 2000 comets are known with retrograde orbits, and some 100 minor planets. Retrograde (nearly polar) TNOs have been found more recently. The first, 2008 KV<sub>42</sub> (‘Drac’, Gladman et al., 2009) and the second, 2011 KT<sub>19</sub> (‘Niku’, Chen et al., 2016), have long dynamical lifetimes of order 1 Gyr. They may originate from the Oort cloud, rather than the scattered disk (Brasser et al., 2012b; Rabinowitz et al., 2013; Volk & Malhotra, 2013), perhaps related to the hypothesised Planet Nine (Shankman et al., 2017).

### 12.5.10 Planetary satellites

All solar system planets, apart from Mercury and Venus, possess satellites. They are believed to have formed through one of three principal processes (Stevenson et al., 1986; Peale, 1999): as a by-product of planetary formation in a circumstellar disk (the *regular satellites*), through capture (the *irregular satellites*), or as a result of massive impacts (like the Moon, §12.3.3).

**Regular satellites** Planet formation, whether by core accretion or gravitational instability, is assumed to be accompanied by collapse of the gaseous envelope into a sub-disk (box, page 463), forming the *regular satellites* by coagulation processes similar to those in the protoplanetary disk itself (Lubow et al., 1999; Mosqueira & Estrada, 2003b,a; Alibert et al., 2005b; Lubow & D’Angelo, 2006; Raymond et al., 2006c; Canup & Ward, 2006; Scharf, 2008; Sasaki et al., 2010; Kane et al., 2013b; Fujita et al., 2013; Makalkin & Dorofeeva, 2014; Tanigawa et al., 2014; Heller & Pudritz, 2015; Miguel & Ida, 2016; Shibaie et al., 2017; Suetsugu & Ohtsuki, 2017). The regular satellites then typically follow prograde orbits, with small orbital inclination or eccentricity.

Specifically, around gas giants, the subset of ‘regular’ prograde satellites are thought to form in circumplanetary disks. The prograde motion is driven by gas inflow in the leading horseshoe region and gas outflow

**Near-Earth Objects (NEOs, NEAs, and PHAs):** Near-Earth Objects (NEOs) are asteroids and (short-period,  $P < 200$  yr) comets with pericentre  $q < 1.3$  au. Details of the ongoing search programmes (notably the Catalina Sky Survey, Pan-STARRS, LINEAR, Spacewatch, and NEOWISE), and discovery statistics, are given at [neo.jpl.nasa.gov/neo](http://neo.jpl.nasa.gov/neo). The 10 000th NEO, asteroid 2013 MZ5, was detected by Pan-STARRS-1 in June 2013.

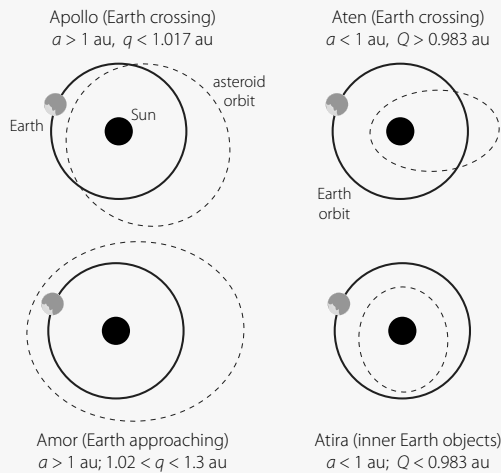
The majority of NEOs are asteroids (Near-Earth Asteroids, or NEAs) rather than comets. NEAs are further subdivided into groups according to perihelion ( $q$ ), aphelion ( $Q$ ), and semi-major axis ( $a$ ):

**Apollos** (prototype 1862 Apollo): Earth-crossing with  $a > 1$  au ( $q < 1.017$  au,  $a > 1.0$  au)

**Atens** (prototype 2062 Aten): Earth-crossing with  $a < 1$  au ( $Q > 0.983$  au,  $a < 1.0$  au)

**Amors** (prototype 1221 Amor): Earth-approaching, orbit between Earth and Mars ( $q = 1.017 - 1.3$  au,  $a > 1.0$  au)

**Atiras** (prototype 163693 Atira; aka inner Earth objects): orbits entirely within Earth's ( $Q < 0.983$  au,  $a < 1.0$  au)



Potentially Hazardous Asteroids (PHAs) are a 'potentially threatening' subset of NEAs, somewhat arbitrarily defined as having minimum orbit intersection distance with Earth  $< 0.05$  au, and absolute magnitude  $H < 22.0$  mag (corresponding to  $D > 150$  m for an assumed albedo of 0.13). As of March 2015, there were 1555 known PHAs.

in the trailing horseshoe region, yielding satellite orbits aligned with the planetary spin axis (e.g. Tanigawa et al., 2014). The orbits can subsequently be modified by secular spin-orbit interactions (e.g. Ward & Hamilton, 2004).

**Detailed models** Such disk models can reproduce close-in multiple moons as in the solar system, both in terms of location (Mosqueira & Estrada, 2003a; Sasaki et al., 2010) and total mass (Canup & Ward, 2006; Sasaki et al., 2010).

Some theories distinguish between a young sub-disk, fed by radial and vertical infall from the protoplanetary gas and dust, and a late sub-disk in which the gas has dispersed (Canup & Ward, 2002; Alibert et al., 2005b; Canup & Ward, 2006). Others argue for late-stage gas-poor planetesimal capture (Estrada & Mosqueira, 2006). Layered accretion disks with dead zones (§10.3.4) might be favoured (Lubow & Martin, 2013).

Again, and in analogy with current planet formation and migration theories, satellites which form during the young disk phase may migrate inwards and be accreted by the planet (Spalding et al., 2016). Surviving satellites may then simply be the last objects to form in the disk, a process which may lead to a general scaling law between the host planet mass and the total satellite mass (Canup & Ward, 2006). Their models consistently produced satellite masses totaling a few  $10^{-4} M_p$ .

In the solar system, there are at least 55 regular satellites: one of Earth, eight of Jupiter, 22 named regular moons of Saturn (plus innumerable moonlets), 18 of Uranus, and 6 small regular moons of Neptune. Neptune's largest, Triton, appears to have been captured. Of the dwarf planets, Pluto's five moons (§12.5.1), and Haumea's two, are believed to have formed in orbit out of giant collisional debris.

**Irregular satellites** In the solar system, there are more than 100 *irregular satellites* orbiting the four giant planets (Jupiter, Saturn, Uranus and Neptune), the largest of each being Himalia (Li & Christou, 2016), Phoebe (Castillo-Rogez et al., 2012), Sycorax (Romon et al., 2001), and Triton (Gaeman et al., 2012) respectively.

Irregular satellites are believed to have been captured by their parent planet, possibly leading to planet-satellite systems with distinct chemical compositions (Huang & Innanen, 1983). The orbit direction of a captured body depends on the approach trajectory, with both prograde or retrograde orbits possible (Agnor & Hamilton, 2006; Lewis & Fujii, 2014; Ochiai et al., 2014; Tanigawa et al., 2014).

**Detailed models** Irregular satellites are loosely identified by their distant, inclined, and often eccentric and retrograde orbits, and more objectively if their orbital precession is controlled primarily by the Sun. They appear as dormant comet-like objects that occupy both stable prograde and retrograde orbits, with retrograde substantially outnumbering prograde.

Many appear to have been captured from heliocentric orbits near their current locations, shortly after the formation of their parent planet, with more recent simulations reproducing appropriate capture efficiencies (Sheppard & Jewitt, 2003; As-takhov & Farrelly, 2004; Holman et al., 2004; Sheppard et al., 2006; Koch & Hansen, 2011; Gaspar et al., 2011, 2013; Nesvorný et al., 2014b; Ochiai et al., 2014; Higuchi & Ida, 2016).

Others may have been dynamically captured during the same planetesimal-dominated orbital migration phase of the outer planets (§12.6), in which multiple close encounters between the giant planets allowed scattered comets to be captured via three-body interactions (Agnor & Hamilton, 2006; Bottke et al., 2010). Analogous binary planetesimal exchange reactions have been assessed for the capture of irregular satellites in other migrating planetary systems (Quillen et al., 2012).

Orbits may have been subsequently affected by satellite-satellite interactions and resonances, such processes affecting systems including Jupiter (Nesvorný et al., 2003; Ogihara & Ida, 2012; Fuller et al., 2016), Saturn (Fuller et al., 2016; Ćuk et al., 2016a), and Pluto (Youdin et al., 2012; Pajola et al., 2012).

Simulations confirm that the irregular moons are on largely stable orbits despite substantial perturbations near apocentre (Hamilton & Burns, 1991). Retrograde orbits are more stable than prograde due to increased relative Hill stability (Hamilton & Burns, 1991; Nesvorný et al., 2003), while inclinations between  $50 - 130^\circ$  are highly unstable due to Lidov-Kozai oscilla-

tions (§10.10.6; Carruba et al., 2002; Nesvorný et al., 2003). Unlike the regular satellites, and due to their larger separations, irregular satellites are rarely tidally locked.

Sizes show power-law distributions, while some orbit in dynamical ‘groups’, collisionally-generated families which were parts of a larger body that fragmented (Nesvorný et al., 2004). Statistics of the captured satellites, including size distributions and numbers of prograde and retrograde orbits, provide specific tests for theories of planetary formation.

Of irregular satellites, Triton was imaged by Voyager 2 in 1989 (Tyler et al., 1989), and Phoebe by Cassini in 2004 (Castillo-Rogez et al., 2012); the inferred cratering rates constrain its origin (di Sisto & Brunini, 2011).

**Massive impacts** For terrestrial planets below  $\sim 2.5M_{\oplus}$ , giant impacts can be sufficiently energetic to place up to 4% of the planet’s mass into orbit (Canup et al., 2001), but not energetic enough to disperse the disk out of which one or more protomoons can form (Wada et al., 2006). Due to gravitational perturbations from planetary tides (Atobe & Ida, 2007), or between protomoons (Canup et al., 1999), only systems with single moons on co-planar orbits, or close inclined orbits, can survive the planet–moon or moon–moon collisions.

**Challenges to understanding** Amongst an essentially indefinite number of unknowns relating to the solar system satellites, the following is a subjective and incomplete selection.

The detailed origin of Mars’ moons, Phobos and Deimos, remains an open issue. None of the proposed scenarios (intact capture of two distinct outer solar system small bodies, co-accretion with Mars, and accretion within an impact-generated disk) fully reconcile their orbital and physical properties (e.g. Craddock, 2011; Rosenblatt, 2011; Ronnet et al., 2016; Hyodo et al., 2017b; Hansen, 2018). The ‘parallel grooves’ on Phobos, whether secondary impact chains, fracture plains, clastic ejections and/or Stickney crater related, are a striking and still-debated feature (e.g. Veverka & Duxbury, 1977; Ramsley & Head, 2013; Murray & Heggie, 2014; Simioni et al., 2015; Wilson & Head, 2015; Bruck Syal et al., 2016).

To address problems with more conventional disk-based models, Asphaug & Reufer (2013) suggested that Saturn originally had a system of moons comparable to Jupiter’s Galilean satellites, that collided and merged, ultimately forming Titan. They reasoned that medium-sized moons were spawned in a few such collisional mergers, liberating ice-rich spiral arms that self-gravitated into escaping clumps, while Jupiter’s original satellites stayed locked in resonance.

Saturn’s Iapetus displays a number of unusual surface features, notably a high equatorial ridge, and a large flattening inconsistent with its current spin rate. Its large orbit inclination combined with its low eccentricity suggest excitation through early solar system encounters, and various models for its formation and evolution have been proposed (Rivera-Valentin et al., 2014; Nesvorný et al., 2014c; Kuchta et al., 2015).

Saturn’s Enceladus also challenges detailed models. Mostly covered by ice, other features range from old heavily-cratered regions to young tectonically-deformed terrain. Cassini discovered  $H_2O$ -rich plumes venting from the south polar region, pointing to escaping internal heat and ongoing geological activity. Like various other giant planet satellites, Enceladus is in an orbital resonance (with Dione), which excites its eccentricity, which is damped by tidal forces. These *eccentricity*

**Naming of satellites, asteroids, and rings:** Since 1973, the naming of solar system satellites, asteroids, Kuiper belt objects, rings and divisions has been under the IAU Working Group for Planetary System Nomenclature, WGPSN (Table 1.4). Roman-numeral satellite designations were first adopted with the discovery of the Galilean moons, although confusion arose through their re-numbering, counting outwards, with each new discovery. Today, satellite discoveries are given provisional designations such as ‘S/2003 S1’ (the first Saturn discovery in 2003), with a permanent name assigned once confirmed and its orbit computed. Until 2015, names were assigned to all moons discovered, regardless of size. Since then, eight small Jovian satellites (Jupiter LI, LII, and LIV–LIX) have received permanent Roman-numeral designations but not names.

*tides* heat its interior, and possibly drive geological activity (e.g. Lainey et al., 2012; Rambaux & Castillo-Rogez, 2013; Spencer & Nimmo, 2013; Iess et al., 2014; Travis & Schubert, 2015; Baland et al., 2016). Its irregular shape has been attributed to multiple low-energy impactors (Monteux et al., 2016b).

Saturn’s inner moons interior to and including Tethys are 90% ice, while its outer neighbour Dione is >40% rock. Formation models invoke a combination of resonantly captured icy ring material, and delivery of rock by cometary impactors during a late heavy bombardment (Salmon & Canup, 2017).

Of the five ‘round’ Uranian satellites, Miranda, discovered in 1948, is the innermost, just 500 km in size, and the least dense. Current understanding of its large orbit inclination ( $4^{\circ}3'$ ) is that the moons occasionally pass through various secondary resonances (Malhotra & Dermott, 1990; Peale, 1988a; Tittemore & Wisdom, 1988, 1990; Verheylewewen et al., 2013; Verheylewewen & Lemaître, 2014) which, at some point, led to it being locked into a 3:1 resonance with Umbriel, before chaotic behaviour induced by the secondary resonances released it (Tittemore & Wisdom, 1989; Moons & Henrard, 1994). Tidal heating during its Umbriel resonance would have driven intense geological activity, resulting in the deep-fractured surface (Dermott et al., 1988), including coronae, canyons and 5-km high cliffs, imaged by the Voyager 2 fly-by in 1986 (Smith et al., 1986).

### 12.5.11 Trojans

Trojan minor planets or moons share the orbit of a planet or larger moon, occupying the stable Lagrange points L4 (leading) or L5 (trailing) of the larger body. They may be primordial, a frequent by-product of planet formation (e.g. Beaugé et al., 2007), or subsequently captured (e.g. Morbidelli et al., 2005; Schwarz & Dvorak, 2012; Nesvorný et al., 2013b). Along with the main asteroid belt and the Kuiper belt, Trojans represent the only stable equilibrium orbits for small solar system bodies.

**Solar system Trojans** The Jupiter Trojans account for most known Trojans in the solar system. They are divided into the Greek (L4) and Trojan (L5) camps. More than 6000 have been found, with more than  $10^6$  larger than 1 km thought to exist (e.g. Marzari & Scholl, 2002; Freistetter, 2006; Emery et al., 2011; Yoshida & Terai, 2017). Rotational properties can be characterised from photometric light curves (Mottola et al., 2011), most recently from Kepler Campaign 6 (Szabó et al., 2017). They show a bimodal colour distribution (Wong & Brown, 2016),

traced to their primordial progenitor populations (with depletion or retention of H<sub>2</sub>S surface ice) after which scattering and repopulation occurred during the period of dynamical instability of the outer solar system (§12.6). Thersites, presently at L<sub>4</sub>, is a potentially *jumping Trojan*, possibly dynamically destined for L<sub>5</sub> (Tsiganis et al., 2000).

There are also a small number of Mars Trojans (Bowell et al., 1990; Todd et al., 2012; de la Fuente Marcos & de la Fuente Marcos, 2013b), and Neptune Trojans, 7 and 17 respectively as of the end of 2017. The first Neptune Trojan was discovered through the Deep Ecliptic Survey (2001 QR<sub>322</sub>, Chiang et al., 2003), with subsequent discoveries (leading and trailing) including the high-inclination 2005 TN<sub>53</sub>, indicative of capture rather than primordial formation (Sheppard & Trujillo, 2006; Dvorak et al., 2007; Zhou et al., 2011; Lykawka et al., 2011).

Dynamical simulations suggest that Saturn and Uranus do not possess primordial Trojans, at least in large numbers (Sheppard & Trujillo, 2006; Dvorak et al., 2010a). Nonetheless, Alexandersen et al. (2013) detected the first Uranian Trojan, 2011 QF<sub>99</sub>, and demonstrated that it oscillates around the Uranian L<sub>4</sub> Lagrange point for >70 000 yr, and remains co-orbital for ~1 Myr, before becoming a Centaur.

The discovery of the first (and to date only) Earth Trojan, the 300-m diameter 2010 TK<sub>7</sub>, located at L<sub>4</sub>, was discovered using WISE, and is considered dynamically stable over > 10<sup>4</sup> yr (Connors et al., 2011; Marzari & Scholl, 2013).

A few long-lived *horseshoe* companions to Earth, viz. encompassing L<sub>3</sub>, L<sub>4</sub> and L<sub>5</sub>, are also known, including the first, 3753 Cruithne (Wiegert et al., 1997), 2002 AA<sub>29</sub> (Connors et al., 2002), 2010 SO<sub>16</sub> (Christou & Asher, 2011), and 2013 BS<sub>45</sub> (de la Fuente Marcos & de la Fuente Marcos, 2013a).

Trojan moons also exist, all in the Saturn system: Telesto and Calypso of Tethys, and Helene and Polydeuces of Dione.

### 12.5.12 Planetary rings

Planetary ‘rings’, as a subsets of disks, are characterised by large planet/ring mass ratios that drive their flatness, with aspect ratios as small as 10<sup>-7</sup> (Esposito, 2002, 2006; Tiscareno, 2013b). The most prominent are those around Saturn, but the other giant planets also have ring systems. Rings or disks are also known around brown dwarfs (§9.8.1) and minor planets.

Some are associated with *shepherd moons*, small satellites near their inner or outer edges, or within gaps, and whose gravity induces a sharply-defined edge to the ring. Saturnian shepherd moons include Prometheus, Daphnis, Pan, Janus, and Epimetheus (for the exchanging Trojan orbits of Janus–Epimetheus, see box, page 74); Uranian shepherds include Cordelia and Ophelia.

Rings serve as laboratories for understanding many detailed gravitational and dynamical phenomena, and as models for the photometric signatures that should exist around transiting exoplanets (§6.14.5). Planetary rings are the most nearby astrophysical disks, and the only ones to have been examined by proximate spacecraft. Many advances have been made by HST, with many more expected with JWST (Tiscareno et al., 2016).

**Formation** There are three main processes by which planetary rings are believed to form (e.g. Charnoz et al., 2017): from protoplanetary disk material within the planet’s Roche limit; from the debris of an impact-disrupted moon; or from tidally-disrupted debris of an object within the planet’s Roche limit, either a moon (e.g. Leinhardt et al., 2012), or a body scattered from the primordial Kuiper belt, possibly during the Late Heavy Bombardment (Hyodo et al., 2017a). Fainter rings can form as a result of meteoroid impacts (e.g. Tiscareno et al., 2013) or, in case of Saturn’s E-ring, the ejecta of cryovolcanic material (Spahn et al., 2006).

The composition of ring particles varies; they may be silicate or icy dust. The maximum size of a ring particle is determined by the material’s specific strength, its density, and the relevant tidal force, with boulders up to 10-m in size inferred (Baillié et al., 2013). All known ring systems also include a substantial component of diffuse dust. Narrow dusty rings host azimuthally confined arcs at Neptune, Saturn, and Jupiter.

Ages of self-sustained ring systems vary; some are likely to have formed in the early solar system, while others may be younger and less enduring (Esposito, 2002).

**Solar system planetary rings** Rings are known around all the giant planets. Saturn’s are the most extensive and complex, studied intensively since the time of Galileo (ADS lists several hundred publications since 2000), although their origin remains uncertain (Hyodo & Charnoz, 2017). Detailed studies have been enabled by Cassini, the fourth Saturn probe, and the first to enter orbit. It has studied the planet and its many natural satellites since arrival in 2004 (the mission being extended as Cassini Equinox 2008–10, and Cassini Solstice 2010–17), with the mission terminating, after various disk fly-throughs, on 2017 September 15 (e.g. Nicholson et al., 2008). The rings comprise a disk of varying density, consisting mostly of H<sub>2</sub>O-ice and trace amounts of rock, with particles ranging from  $\mu\text{m}$  to meters (e.g. Zebker et al., 1985; French & Nicholson, 2000; Porco et al., 2005; Nicholson et al., 2008; Charnoz et al., 2009; Verbiscer et al., 2009; Cuzzi et al., 2010; Becker et al., 2016).

Compared to the dense main rings extending out to  $2R_{\text{Saturn}}$ , the outermost Phoebe ring is vast debris disk, extending to some  $260R_{\text{Saturn}}$ , that also appears to be collisionally generated by its irregular satellites (Tamayo et al., 2016a).

The Saturn A–C rings, and the Cassini Division (e.g. Hedman et al., 2010), host many phenomena of general application to disks including resonances, spiral waves, gap formation, self-gravity wakes, viscous overstability and normal modes, impact clouds, issues of shepherding and confinement, and the orbital evolution of embedded moons (e.g. Tiscareno, 2013b; French et al., 2017; Seiß et al., 2017; Tajeddine et al., 2017; Voitko & Troianskiy, 2017). They also serve as detectors of Saturn’s internal oscillation modes, through *kronoseismology* (§8.6.4).

The Uranian rings were discovered by Elliot et al. (1977). Subsequent observations, mainly by Voyager 2 (e.g. Smith et al., 1986; Chancia & Hedman, 2016), and HST (e.g. Showalter & Lissauer, 2006), reveal some 13 distinct rings, mostly opaque and a few km wide. They are dark, and comprise H<sub>2</sub>O-ice and radiation-processed organics. The relative lack of dust is due to aerodynamic drag from the extended corona of Uranus.

Jupiter's ring system was first observed by Voyager 1 (Smith et al., 1979; Showalter et al., 1987), and subsequently by Galileo (Ockert-Bell et al., 1999). Its main parts consist primarily of dust: a faint thick 'Halo' torus, a thin relatively bright 'Main' ring, and two faint 'Gossamer' rings (Esposito, 2002). The Neptune system comprises five principal dust rings, long-suspected prior to confirmation by Voyager 2 (Smith et al., 1989).

**Other bodies** Ring systems have been found from stellar occultation for the dwarf planet Haumea (Ortiz et al., 2017), and for two minor planets: the Centaurs 10199 Chariklo (Bragaribas et al., 2014; Kondratyev, 2016; Pan & Wu, 2016; Araujo et al., 2016; Bérard et al., 2017; Wood et al., 2017). and 2060 Chiron (Ortiz et al., 2015a; Wood et al., 2018). Centaur rings are attributed to tidal disruption of a differentiated body during close encounter with a giant planet (Hedman, 2015; Hyodo et al., 2016). The 'firefly' rings of the Janus–Epimetheus system have a short dynamical life time,  $\lesssim 20$  yr, and are likely replenished by micrometeorite satellite impacts (Winter et al., 2018b). Rings have been postulated but ruled out for Pluto (Steffl & Stern, 2007; Lauer et al., 2018) and Rhea (Tiscareno et al., 2010a).

**Propeller moons** Within Saturn's A Ring, S-shaped density structures, several km across and termed *propellers*, were found in Cassini images (Tiscareno et al., 2006). Previously predicted (Spahn & Sremčević, 2000; Sremčević et al., 2002), more than 150, localised in two regions, are now known (Sremčević et al., 2007; Tiscareno et al., 2008, 2010b).

**Moonlets** N-body simulations show that they are partial gaps in the surrounding material generated by gravitational interaction with small (undetected) 100-m sized embedded moons, or *moonlets* (Seiß et al., 2005; Sremčević et al., 2007; Lewis & Stewart, 2009; Rein & Papaloizou, 2010; Michikoshi & Kokubo, 2011). Hydrodynamic simulations (Seiß et al., 2017), previously used to study evolution of planetary embryos in protoplanetary disks (e.g. Kley, 1999; Lubow et al., 1999), provide further insight into the resulting density patterns.

The largest example, *Blériot*, has been tracked in the Cassini images for several years. The moonlet's inferred orbital evolution shows non-Keplerian longitudinal motion (Tiscareno et al., 2010b). Various models have attributed this to a specific co-orbital ('frog') resonance (Pan & Chiang, 2010; Pan et al., 2012; Pan & Chiang, 2012), to a pressureless form of type I migration (§10.10.2; Crida et al. 2010a) in which torques due to local density fluctuations act to keep the embedded moon's semi-major axis at an equilibrium position (Tiscareno, 2013a), or to a type of forced libration (Seiler et al., 2017). Another well-studied propeller is Earhart (Hoffmann et al., 2013, 2015).

**Exoplanet systems** Because all solar system giant planets have rings, the existence of exoplanet rings is also considered highly probable (§6.14.5).

Occultations of 1SWASP J1407 (strictly 1SWASP J140747.93–394542.6) observed in 2007 (§6.14.6) have been interpreted as a ring system but, because of its youth, one likely due to a protoplanetary disk rather than to a stable ring in an evolved planetary system.

### 12.5.13 Zodiacal dust

The smallest component of the solar system's minor bodies is dust, which broadly traces a flattened cloud in

the plane of the ecliptic. Sunlight scattered from the dust is responsible for *zodiacal light*, the roughly triangular white glow visible in the night sky that appears to extend from the vicinity of the Sun along the ecliptic (or zodiac).

Zodiacal dust is an important constituent of the Sun's debris disk. It comprises asteroidal and cometary debris (Reay & Ring, 1968), as well as a small contribution of interstellar origin. Different contributions dominate at different heliocentric distances (e.g. Rowan-Robinson & May, 2013): dust in the inner solar system is mainly attributable to Jupiter-family comets, asteroids, Halley-type comets, and Oort cloud comets (Carrillo-Sánchez et al., 2016), while a specific component is associated with the Edgeworth–Kuiper belt (§12.5.6).

Understanding and quantifying the dust component is important in interpreting the solar system's origin and evolution (e.g. in the context of the Nice model, §12.6; Booth et al., 2009), in assessing background light contributions in other systems to exo-Earth imaging (e.g. Ishiguro & Ueno, 2003, see also Section 7.5.3), and for insights into the origin, morphology and dynamics of exoplanetary debris disks (§10.6).

**Early models** Early models of the scattered optical zodiacal light (reviewed by Leinert, 1985; Giese et al., 1986) led to a picture in which the number density of dust grains in the inner solar system followed a smooth distribution, separated into radial and vertical dependences

$$n(R) = n_0 R^{-\gamma} f(\beta_0), \quad (12.5)$$

where  $R$  is the heliocentric distance in au,  $\gamma \sim 1.3$ , and  $f(\beta_0)$  is formulated in terms of the elevation angle from the dust's symmetry plane. Various refinements of a simplified 'fan-like' form,  $f(\beta_0) = \exp(-P|\sin \beta_0|)$ , can be found in the literature (e.g. Kelsall et al., 1998; Mann, 2010; Rowan-Robinson & May, 2013).

The radial term,  $R^{-\gamma}$ , reflects the expected distribution for particles affected by *Poynting–Robertson drag*: viz. for dust grains of diameter  $\sim 1$ – $100 \mu\text{m}$ , radiation pressure tangential to their orbital motion introduces a 'drag' force, and the grains spiral slowly towards the star (smaller grains are blown outward by radiation pressure, while larger grains are halted by collisions).

**Insights from IRAS** The IRAS mission (1983) gave the first all-sky maps of the zodiacal dust emission. In addition to a smooth underlying cloud, the data revealed a number of dust 'bands' (the IRAS zodiacal bands), attributed to collisions between members of asteroid families (Dermott et al., 1984; Low et al., 1984; Sykes & Greenberg, 1986; Sykes, 1990; Rowan-Robinson et al., 1991; Grogan et al., 2001). At least five asteroid families are now known, contributing  $\sim 10\%$  of the total infrared zodiacal emission (Divine, 1993). The data also revealed, on a smaller scale, cometary dust trails (Sykes et al., 1986). Together, these demonstrated that collisions between asteroidal and cometary debris both contribute to the zodiacal dust cloud.

IRAS also revealed a local circumsolar dust ring near the Earth, at some 10% above the background (Dermott et al., 1994; Reach et al., 1995), whose origin is described further below.

Liou et al. (1995) used a dynamical analysis of the IRAS data to conclude that 74% of the zodiacal cloud was of cometary origin, while 26% was asteroidal. Durda & Dermott (1997) concluded that  $\sim 34\%$  could be asteroidal. Nesvorný et al. (2010)

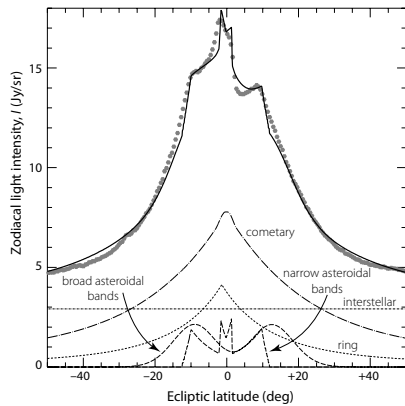


Figure 12.17: Zodiacal light model fit to the IRAS scans at  $\lambda = 25 \mu\text{m}$  (circles), at solar longitude  $90^\circ.6$ . The smooth ‘fan’ component has been subtracted, with the other modeled contributions indicated. These arise from cometary dust, the broad and narrow asteroidal bands, the circumsolar ring associated with the Earth, and an interstellar dust component. From Rowan-Robinson & May (2013, Figure 3a), © Oxford University Press.

modeled the dynamics of cometary dust, concluding that over 90% of zodiacal dust is cometary.

**Other spacecraft results** *In situ* measurements by Ulysses (1990–2009), Galileo (1989–203), Cassini (1997–2017), and Stardust (1999–2011) demonstrated the significant contribution of interstellar dust in the solar system, especially at larger heliocentric distances (e.g. Grun et al., 1993; Mann, 2010; Sterken et al., 2015). Observations from the COBE–DIRBE instrument (1989–90) were modeled by Kelsall et al. (1998) using a modified exponential fan function extending to 5.2 au, but ignoring cometary or interstellar dust.

Rowan-Robinson & May (2013) modeled the combined IRAS and COBE–DIRBE observations with the aim of estimating the relative contributions of asteroidal, cometary and interstellar dust to the zodiacal cloud. They identified an isotropic component of foreground radiation attributable to interstellar dust. The interstellar dust grains are expected to be smaller than those of cometary and asteroidal origin, and are indeed found to be so in spacecraft studies (e.g. Grun et al., 1993). Rowan-Robinson & May (2013) derived a modeled grain radius for the interstellar dust component of 2–4  $\mu\text{m}$ .

In the ecliptic plane at  $r = 1.53$  au, they estimated the mass density in grains (in terms of some characteristic grain radius and absorption efficiency) as  $\rho \sim 10^{-23.27} \text{ Mg m}^{-3}$  for the fan,  $10^{-25.27}$  for the interstellar dust, and  $10^{-23.67}$  for the cometary dust. They concluded that the zodiacal dust cloud is supplied by a combination of cometary dust (60–80%), dust from collisions between members of asteroid families in the asteroid belt (20–40%), and interstellar dust (20–40%). It therefore carries detailed information about the recent history of the Sun’s debris disk. In their model, 1% of the zodiacal dust arriving at Earth would be interstellar.

Other space-based observations have come from ISO (e.g. Müller et al., 2005b), and from Planck (Ade et al., 2014).

**Coronal mass ejections** From the Akari infrared mission (2006–11, formerly IRIS and ASTRO-F), clouds of smaller dust particles, possibly nm-sized glassy carbon, are inferred to originate from solar coronal mass ejections (Ishihara et al., 2017a).

**Dust motion and resonances** The density of interstellar dust in the solar system varies with time, dependent on the solar cycle. Because the dust particles become charged, their motion is strongly influenced by the plasma flow, and the Earth’s bow shock excludes much of the dust, especially the smaller particles. At times of solar maximum, magnetic field reversals allow interstellar dust into the inner solar system. Its velocity relative to the Sun,  $\sim 26 \text{ km s}^{-1}$ , means that this dust can cross the  $\sim 200$  au from the magnetopause in  $\sim 50$  yr. In contrast, dust in approximately circular orbit around the Sun, and (for sizes 1–100  $\mu\text{m}$ ) spiraling inwards due to Poynting–Robertson drag (and, to a lesser extent, solar wind drag) takes  $\sim 10^4$  yr to travel from the asteroid belt to the Earth (Wyatt & Whipple, 1950; Burns et al., 1979; Gustafson et al., 1987). Other effects include gravitational trapping by the Sun with a time-scale of  $\sim 2$  yr (Rowan-Robinson & May, 2013).

Although planets have a negligible effect on the motion of interstellar dust, inwardly spiraling dust crosses locations where it can be trapped (for  $10^4 - 10^5$  yr) into particular orbital resonances. Multiple resonances can combine to form a dust ring, with non-uniform azimuthal distribution (e.g. Weidenschilling & Jackson, 1993; Mustill & Wyatt, 2011).

Such rings were predicted to be associated with the Earth by Jackson & Zook (1989), and subsequently observed by IRAS (Dermott et al., 1994). A similar circumsolar dust ring associated with Venus was revealed by STEREO (Jones et al., 2013a).

#### 12.5.14 Interstellar vagabonds

Gravitational scattering during planet formation inevitably implies that interstellar space should be populated with extrasolar planetesimals and comets. Created in, and ejected from, other systems, they have been termed *interstellar vagabonds* (Mamajek, 2017). Passing through it, they would be distinguishable from bodies of solar system origin ( $e \lesssim 1$ ) by their hyperbolic orbits ( $e \gg 1$ ) resulting from the Sun’s velocity with respect to the Local Standard of Rest (although see Wiegert, 2014). Their detection and characterisation would provide further information on planet formation (cf. box, page 282).

**Early searches** Early searches failed to identify plausible candidates. McGlynn & Chapman (1989) noted the lack of detections based on a model with a stellar space density of  $0.1 \text{ pc}^{-3}$ , each system ejecting  $10^{14}$  planetesimals into interstellar space. Jewitt (2003) argued that if each star ejects  $10^{13}$  km-sized planetesimals, resulting in a space density of  $10^{-3} \text{ au}^{-3}$  and a velocity relative to the Sun of  $20 \text{ km s}^{-1}$ , some  $0.3 \text{ yr}^{-1}$  would pass within 5 au. Because a 1-km size object at 5 au corresponds to  $\sim 24$  mag, he considered it unsurprising that none have been found. Pan–STARRS might detect a few in its 10-yr lifetime.

Revised estimates were made by Moro-Martín et al. (2009), based on improved models of debris disks, planetesimal scattering, and expected size distribution, assuming albedos of 6% (similar to inactive comets). They conclude that the absence of detections was not in contradiction with current knowledge, while the probability that LSST will detect a single *inactive* exocomet during its lifetime is below 1%. The detection probability is somewhat larger for objects close to the Sun, both as a result of increased gravitational focusing, and increased activity. Other estimates have since been made (Engelhardt et al., 2017; Trilling et al., 2017; Do et al., 2018).



Early candidates C/2007 W1 (Boattini; Królikowska & Dybczyński, 2013; Dybczyński & Królikowska, 2015) and C/1853 E1 (Secchi; Branham, 2012), were rejected by Cook et al. (2016).

**11/2017 U1 (Oumuamua)** Oumuamua was discovered with Pan-STARRS (R. Weryk) on 2017 October 18, some 40 d after pericentre (within the orbit of Mercury), at  $V = 22$  mag (Meech et al., 2017). It is a minor body some 100-m in size, and on a hyperbolic orbit with  $e = 1.192 \pm 0.003$  (the highest known), and  $v_\infty = 26 \text{ km s}^{-1}$ .

It was originally provisionally designated as comet C/2017 U1, and later as asteroid A/2017 U1. Once confirmed as originating outside the solar system a new minor body designation was created: I for Interstellar object, and it was numbered 1I as the first so identified. It was named ‘Oumuamua from the Hawaaiian for ‘scout’, transliterated here, without the ‘okina, as Oumuamua.

**Detailed investigations** By the end of 2017, 3 months after discovery, more than 30 studies have examined its orbit (e.g. de la Fuente Marcos & de la Fuente Marcos, 2017b; Mamajek, 2017; Trilling et al., 2017), and its shape, rotation and surface properties from photometry and spectroscopy (Bannister et al., 2017; Fitzsimmons et al., 2018; Jewitt et al., 2017; Knight et al., 2017; Masiero, 2017; Ye et al., 2017; Bolin et al., 2018).

Its possible origin has been variously considered, perhaps connected to the local association, or other specific stellar systems including HIP 103749 or GJ 876 (e.g. Gaidos et al., 2017c; Mamajek, 2017; Wright, 2017; Zuluaga et al., 2017; Do et al., 2018; Dybczyński & Królikowska, 2018; Feng & Jones, 2018a; Zhang, 2018). Its shape and inferred tumbling motion, with a period of  $\sim 8$  h, may imply a collisional or binary ejecta origin (Drahus et al., 2017; Fraser et al., 2017; Jackson et al., 2017a; Ćuk, 2018; Raymond et al., 2018). A suggestion that it could be macroscopic dark matter was made by Cyncynates et al. (2017). Constraints on radio transmitter power, on the hypothesis that it an ‘alien’ source, have been derived (Enriquez et al., 2018).

Its high axial ratio of  $\geq 5:1$  (Bannister et al., 2017), or perhaps even 10:1 (Meech et al., 2017) may result from its travel through interstellar space for several hundred Myr (Domokos et al., 2017): free from larger impactors, many high-velocity impacts, from  $\mu\text{m}$ -sized interstellar dust grains, would be energetic enough to repeatedly dislodge splinters (§12.5.4). Further evidence for an abrasion history is the inferred lack of dust on its surface (Meech et al., 2017). A fly-by mission to be launched within 5–10 yr has been considered (Hein et al., 2017).

## 12.6 Disk depletion, truncation, and migration

**Structure** The solar system is characterised by a tri-modal structure (Morbidelli & Raymond, 2016). In its inner part are the relatively small rocky terrestrial planets. Beyond lies the asteroid belt, with its rather negligible  $M_{\text{tot}} \sim 5 \times 10^{-4} M_\oplus$ . The giant planets lie beyond 5 au.

The formation of the terrestrial planets requires that, during the lifetime of the protoplanetary disk, a number of planetary embryos formed in that region, with approximately the mass of Mars, with Mars itself perhaps a surviving embryo. The small Mars/Earth mass ratio suggests substantial depletion in the total mass of solid beyond 1 au and across the asteroid belt, established early

**Secular resonances,  $\nu_5$  and  $\nu_6$ :** Due to their mutual gravitational interactions, the elliptic elements of the planetary orbits ( $e, i, \bar{\omega}, \Omega$ ) vary, to a first approximation, as the superposition of harmonics with different constant frequencies (e.g. Morbidelli & Henrard, 1991a, eqn 1). Details depend on the planet masses, orbital configuration, and gravitational potential of the gas disk in which they are embedded (Brouwer & Clemence, 1961; Heppenheimer, 1980; Ward, 1981; Nagasawa et al., 2000). Dominant in the solar system are terms driven by the Sun–Jupiter–Saturn system, with frequencies traditionally referred to as  $g_5, g_6$ , and  $s_6$  (e.g. Froeschle & Scholl, 1989; Morbidelli & Henrard, 1991b; Murray & Dermott, 2000); the first two related to variation of their  $e$  and  $\bar{\omega}$ , the latter to variation of  $i$  and  $\Omega$ .

The planets also perturb the motion of the asteroids, inducing a secular precession of  $\bar{\omega}$  and  $\Omega$ . When these frequencies are commensurable with the frequencies of the planets, the resulting secular resonance can drive particularly strong orbital excitation. The associated frequencies play a major role for asteroid dynamics:  $\nu_5$  and  $\nu_6$  occur when the precession rate of  $\bar{\omega}$  is equal to  $g_5$  or  $g_6$  respectively, while  $\nu_{16}$  is given by the 1:1 commensurability between the precession rate of  $\Omega$  and the frequency  $s_6$ . Their rates are  $\dot{\nu}_5 = 4.30 \text{ arcsec yr}^{-1}$ ,  $\dot{\nu}_6 = 27.77 \text{ arcsec yr}^{-1}$ , and  $\dot{\nu}_{16} = -25.73 \text{ arcsec yr}^{-1}$  (Brouwer & van Woerkom, 1950).

in the solar system’s history (§12.2.1). In contrast, formation of the giant planets requires the accretion of solid cores of  $10 - 20 M_\oplus$  before the removal of gas.

At least two specific inner disk depletion/truncation mechanisms have been proposed to explain this overall structure. In the presence of ‘sweeping secular resonances’, as the gas disk cleared, the inner region was partially cleared by the strong  $\nu_5$  resonance in the dissipating disk. Alternatively, and possibly as part of a larger phase of planet migration, the gas giants themselves may have migrated through the disk, drifting inward to the terrestrial zone and then outward in a ‘Grand Tack’ that cleared material in their path.

### 12.6.1 Sweeping secular resonances

After the formation of the gas giants, the remaining gas disk continues to dissipate through viscous diffusion, photoevaporation, and erosion by a stellar wind (§10.3.6). In the later stages of depletion, the combined gravity of the disk and of the gas giants generates secular resonances in the inner solar system which move inwards as the gas disk dissipates.

As demonstrated through simulations of their effects on massless test particles, these *sweeping secular resonances* dynamically excite the eccentricities and inclinations of small bodies in large parts of the inner solar system (Heppenheimer, 1980; Ward, 1981; Lecar & Franklin, 1997; Nagasawa et al., 2000, 2001; Kominami & Ida, 2004). Also referred to as *dynamical shake-up*, and *secular conduction* (Levison & Agnor, 2003), simulations show that they can also carry embryos and planetesimals to the inner regions as the gas dissipates (Na-

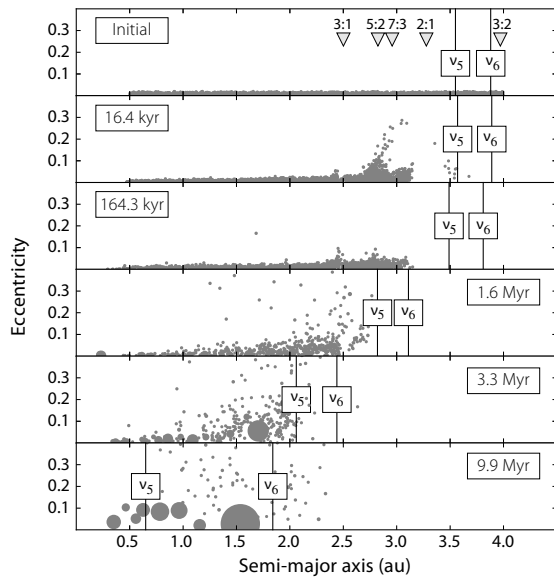


Figure 12.18: Simulations of terrestrial planet formation, showing  $a$  and  $e$  at six time slices, illustrating the effect of sweeping secular resonances. Jupiter and Saturn are on eccentric orbits, corresponding to the present-day solar system. Points represent single bodies with size proportional to mass. Triangles show the location of specific mean motion resonances with Jupiter. Vertical lines indicate the secular resonances  $v_5$  and  $v_6$ , which sweep inwards as the gas disk dissipates. From Hoffmann et al. (2017, Figure 2a), © Oxford University Press.

gasawa et al., 2005; O'Brien et al., 2007; Thommes et al., 2008c; Morishima et al., 2010; Bromley & Kenyon, 2017).

Particularly within the  $v_5$  resonance (box, page 693), where the local apsidal precession rate matches Jupiter's precession rate, orbiting bodies experience repeated eccentricity excitation. As the gas disk dissipates, the location of the inner secular resonance with Jupiter sweeps inward, past the asteroid belt and the terrestrial region, resulting in orbit crossings and protoplanetary collisions. This dynamical 'shake-up' sculpts the inner solar system, inhibiting planet formation in the asteroid belt, and substantially limiting the size of Mars. If the process completes while sufficient gas remains, the planets are also damped to low eccentricities and inclinations through hydrodynamic drag and dynamical friction. This may have left Earth and Venus with their nearly circular and co-planar orbits, while yielding a significant delivery of  $H_2O$ -rich material from the outer asteroid belt as a by-product (§12.1.4).

As an example of recent simulations of terrestrial planet formation with solar system like configurations, Hoffmann et al. (2017) illustrate how migrating giant planets, embedded in a dissipating gaseous disk, influence the dynamics of asteroids, planetesimals, and embryos in the inner solar system, with interactions strongly mediated by mean motion and secular reso-

nances. In all cases, the outer edge of the system is set by the final location of the  $v_6$  resonance, with the mass distribution peaking at the  $v_5$  resonance (Figure 12.18).

**Temporal constraints** Timing is an important constraint for assessing the relevance of this mechanism. Simulations of the inner solar system formation predict that Mars-size protoplanets form on Myr time scales at 1.5 au (Chambers & Wetherill, 1998; Kenyon & Bromley, 2006; Raymond et al., 2009c). Radiometric data support this idea, indicating a fully assembled Mars within  $\sim 4$  Myr (Dauphas & Pourmand, 2011).

Gas dissipation time scales inferred in other systems are  $\sim 1$ – $5$  Myr (§10.3.6). For the solar system, paleomagnetic analyses of volcanic angrites suggests that they formed in a near-zero magnetic field  $4563.5 \pm 0.1$  Ma, 3.8 Myr after solar system formation, and supporting the idea that the solar nebula field, and likely the nebular gas, had dispersed by this time (Wang et al., 2017b). Accordingly, within a few Myr of the collapse of the solar nebula, the gas giants must have formed, the gas disk had dissipated, and Mars was near completion.

The two main timing constraints are then that the gas disk vanishes inside 5–10 au after the formation of Jupiter, and the disk inside the Kuiper belt dissipates on time scales of Myr (Nagasawa et al., 2000). The dissipation rate governs how quickly the  $v_5$  and other resonances sweep through the inner solar system, and for how long individual objects experience the resonance. A rapidly-sweeping resonance may have little effect, while a slow-moving resonance can lead to dynamical ejections. For disk dissipation time scales in the ranges inferred, of  $\sim 1$ – $5$  Myr (§10.3.6) resonances sweep through slowly enough to make an impact, with little sensitivity to the way the disk dissipates (Nagasawa et al., 2000).

With the revised temporal constraints on the formation of Mars, Bromley & Kenyon (2017) reported numerical simulations of planet formation from planetesimals in the terrestrial zone, with the 'dynamical shake-up' sweeping quickly through the solar system, before the formation of Mars is complete. This allows Jupiter's eccentricity pumping to increase fragmentation from high-velocity collisions during the runaway and oligarchic phases. Coupled with the clearing of small debris particles by gas drag and radiation pressure, it naturally inhibits the growth of protoplanets beyond 1 au. The phenomenon likely occurs around other stars with long-period massive planets, suggesting that asteroid belt analogues are common.

**Overlapping resonances** In their present configuration, the outer solar system planets appear to be stable against developing crossing orbits on Gyr time scales, although this is not the case for the inner solar system planets (§12.4.4). On such time scales, chaos is mediated by overlapping resonances, to which minor bodies are particularly sensitive (Chirikov, 1979; Wisdom, 1980; Franklin et al., 1989; Laskar, 1990; Laskar et al., 1992; Morbidelli & Moons, 1993; Moons & Morbidelli, 1995; Murray & Holman, 1997; Nesvorný & Morbidelli, 1998).

Models suggests that overlapping resonances account for the observed distribution of bodies in the asteroid belts (Wisdom, 1982, 1983, 1985; Gladman et al., 1997; Moons et al., 1998), in the inner (Mikkola & Innanen, 1995; Evans & Tabachnik, 1999), and outer solar system (Everhart, 1973; Lecar & Franklin, 1973; Franklin et al., 1989; Gladman & Duncan, 1990; Duncan & Quinn, 1993; Holman & Wisdom, 1993; Holman, 1995; Grazioplene et al., 1999a,b; Morbidelli et al., 2005), as well as within the Kuiper belt (Torbett, 1989; Torbett & Smoluchowski, 1990; Holman & Wisdom, 1993; Levison & Duncan, 1993; Duncan & Levison, 1997; Levison & Duncan, 1997).

### 12.6.2 The case for migration

**Context** The solar system planets have long been considered to have formed more-or-less *in situ*. This paradigm has shifted with the growing evidence for the effects of both gas-driven and planetesimal-driven migration in exoplanet systems (§10.10.2). The former is typically relevant for the 0.1–0.5 Myr of the gas-dominated protoplanetary disk, while the latter operates at later times, after the gaseous disk has dispersed.

The ‘Nice model’, advanced in 2005, was hypothesised in an attempt to reconcile the orbits of the solar system giants with those that would have emerged from the gas-dominated protoplanetary phase (Morbidelli et al., 2007; Raymond et al., 2009c; Morbidelli, 2013). It exploits planetesimal-driven migration, and accordingly operates only after the dissipation of the initial protoplanetary gas disk. It generates the required orbital excitation through a Jupiter–Saturn resonance crossing, possibly accompanied by planetary re-arrangement.

Finding that important features of the *inner* solar system, such as the anomalous mass of Mars and the structure of the asteroid belt, were left unexplained, the ‘Grand Tack’ model of 2011 appealed to an *earlier* phase of gas-driven migration to reconfigure certain features of the inner solar system. Modifications to the original Nice model were introduced to follow the ‘Grand Tack’ with a modified planetesimal-driven migration phase.

**Early concepts** An early argument in support of the existence of planetesimals, and their role in planet formation, is that most bodies in the solar system have evidently been bombarded by objects of comparable size, while some planetesimal-like bodies still remain in the form of asteroids and comets. Further circumstantial evidence appears in the form of observational consequences of disk migration, which has been inferred to take place in many exoplanet systems (§10.10.3).

Evidence for the effects of planetesimal-driven migration, which had been suggested by Safronov (1969), began to emerge from numerical simulations by Fernández & Ip (1984), who found that during an ensemble of such scattering events Jupiter, as the main ejector of planetesimals, loses orbital angular momentum and so moves slightly inwards. On average, Neptune, Uranus, and to some extent Saturn, gain orbital angular momentum in their interactions with planetesimals, and they are displaced more significantly outwards.

A similar migratory effect was proposed for planetary cores which evolved into orbits resembling those of Uranus and Neptune (Thommes et al., 1999).

This type of radial migration could then be responsible for the eccentric orbit of Pluto as a result of resonance capture (Malhotra, 1993a, 1995). As Neptune migrated outwards, it could have captured Pluto and a number of other small Kuiper belt objects into mean motion resonances (§2.12), with the eccentricities of the captured bodies increasing thereafter as Neptune continued its outward migration. For a body captured into resonance, integration of the first-order perturbation equations implies that its eccentricity increases as Neptune’s orbit expands as (Malhotra, 1995, eqn 5)

$$e_{\text{final}}^2 \approx e_{\text{initial}}^2 + \frac{1}{j+1} \ln \left( \frac{a_{\text{N, final}}}{a_{\text{N, initial}}} \right), \quad (12.6)$$

where  $a_{\text{N, initial}}$  is the semi-major axis of Neptune’s orbit at the time of resonance capture,  $a_{\text{N, final}}$  is its final value, and the particle is assumed locked into an exterior  $j+1:j$  orbital resonance.

Accordingly, if Pluto was on an initially circular orbit, and was captured into the 3:2 Neptune resonance, its current  $e = 0.25$  implies that Neptune was at  $a_{\text{N}} \sim 25$  au and Pluto at 33 au at the point of capture, compared with their current locations at 30.1 au and 39.5 au. The large population of Kuiper belt objects in 3:2 resonance with Neptune appears consistent with this same outward migration (Hahn & Malhotra, 2005; Murray-Clay & Chiang, 2005, 2006).

### 12.6.3 The Nice model

With the growing understanding of planetesimal-driven migration, the *Nice model* advanced a scenario for the dynamical evolution of the outer planets (Tsiganis et al., 2005; Morbidelli et al., 2005; Gomes et al., 2005b).

In outline, the process started with a possible ‘initial’ configuration for their orbits at the end of their formation, and after the dissipation of the initial protoplanetary gas disk. Thereafter, a subsequent phase of planetesimal scattering altered their orbits, with the planets migrating from their hypothesised initial configuration into their present orbital positions over a period of some 50 Myr (Figure 12.19). Through this process, the model reconciles the current giant planet orbits with those that would have emerged from the gas-dominated protoplanetary phase.

**Original model** In the original model, the giant planets formed on circular and co-planar orbits, Jupiter started marginally further from the Sun (at 5.45 au, cf. 5.2 au at present), the other giant planets started in a more compact configuration within 17 au, and a large dense disk of small rock and ice planetesimals, of total mass  $30 - 50M_{\oplus}$ , extended from the outermost giant planet to  $\sim 30$  au, with a density falling off linearly with heliocentric distance.

An instability triggered by Jupiter and Saturn crossing their mutual 1:2 mean motion resonance drives the reconfiguration of the outer planets, and is the crucial feature of the Nice model. In some 50% of the initial models, Neptune and Uranus exchange places as a result of this instability (Tsiganis et al., 2005), more in line with models of their formation in a disk that had a surface density that declined with heliocentric distance.

Provided that Jupiter and Saturn crossed their 1:2 resonance on their migratory paths as they interacted with the planetesimal disk, N-body simulations can reproduce a number of primary characteristics of the giant planet orbits, specifically their present semi-major axes and eccentricities, and their mutual inclinations with respect to the mean orbital plane of Jupiter of some  $2^\circ$ .

**Further details** The Nice model begins with some hypothesised starting configuration. Planetesimals at the disk’s inner edge occasionally interact gravitationally with the outermost

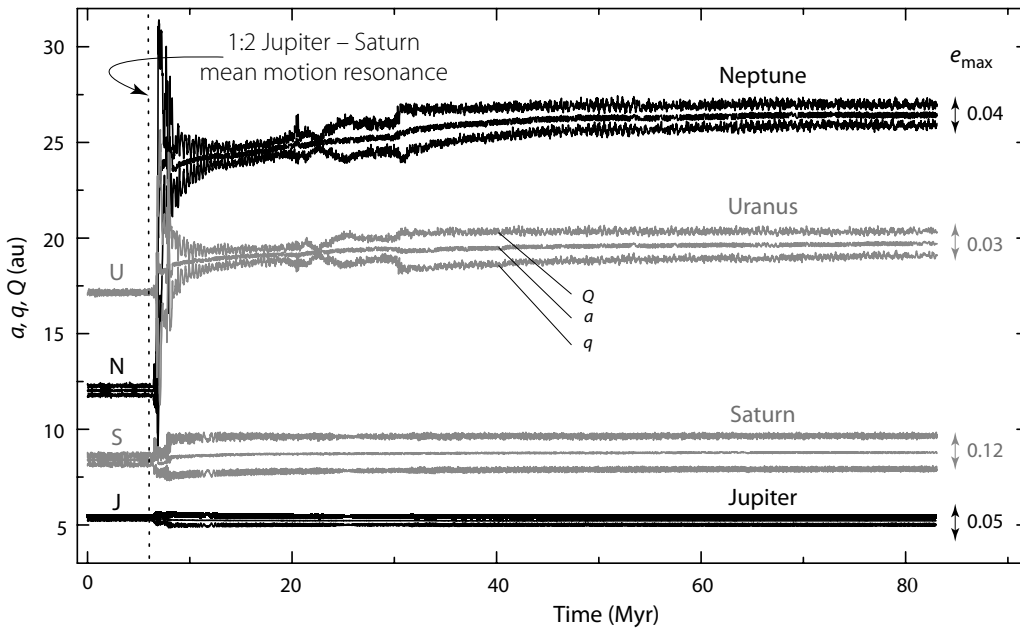


Figure 12.19: Starting configuration of the outer solar system planets in the Nice model, with their subsequent orbital evolution from an  $N$ -body simulation with  $35M_{\oplus}$  of disk planetesimals in 3500 particles out to 30 au. Three curves for each planet indicate the semi-major axis  $a$ , and their minimum ( $q$ ) and maximum ( $Q$ ) heliocentric distances. The vertical dashed line marks the epoch of the 1:2 Jupiter–Saturn mean motion resonance capture. During subsequent interactions, eccentricities of Uranus and Neptune can exceed 0.5. In 50% of simulations, including this one, they exchange orbits. The maximum eccentricity over the last 2 Myr of evolution is indicated. From Tsiganis et al. (2005, Figure 1), by permission from Nature/Springer/Macmillan Ltd, ©2005.

giant planet, which change the planetesimals' orbits. The planets scatter the majority of planetesimals inwards, exchanging angular momentum with the scattered objects so that the planets move outwards. These planetesimals then similarly scatter off the next planet they encounter, so moving the orbits of Uranus, Neptune, and Saturn outwards. The process continues until the planetesimals interact with the innermost and most massive giant planet, Jupiter, which sends them into highly elliptical orbits, or ejects them from the solar system, in turn causing Jupiter to move slightly inwards.

After several Myr of slow migration, Jupiter and Saturn, the two innermost giant planets, cross their mutual 1:2 mean motion resonance. This resonance increases their orbital eccentricities, and destabilises the system. The arrangement of the giant planets alters quickly and dramatically (Figure 12.19). Jupiter shifts Saturn out towards its present position, and this relocation causes gravitational encounters between Saturn and the two ice giants, which propel Neptune and Uranus into more eccentric orbits. These ice giants then interact with the (outer) primordial planetesimal disk, scattering large numbers from their formerly stable orbits in the outer solar system, and removing 99% of its mass, a scenario which explains the observed absence of a dense trans-Neptunian population. Some of the planetesimals are thrown into the inner solar system, producing a sudden influx of impacts on the terrestrial planets, identified with the Late Heavy Bombardment (box, page 669). Eventually, the giant planets reach their current orbital semi-major axes, and dynamical friction with remaining planetesimals damps their eccentricities and circularises the orbits of Uranus and Neptune (Levison et al., 2008).

**Modifications** Modifications of the Nice model have subsequently been considered, including different initial conditions (Morbidelli et al., 2007; Levison et al., 2011), and an early solar system with five (or more) giant planets, one of which is ejected during the instability encounter with Jupiter, and representing a starting configuration with a higher success rate for overall survival (Nesvorný, 2011; Nesvorný & Morbidelli, 2012; Batygin et al., 2012; Nesvorný, 2015b,a; Kaib & Chambers, 2016).

**Jumping Jupiter model** In a subset of the original Nice model simulations, the smooth separation of Jupiter and Saturn is replaced by a series of 'jumps'. This behaviour thereby avoids the sweeping of secular resonances through the inner solar system as their period ratio crosses from 2:1 to 2:3.

In this *jumping Jupiter model* (Brasser et al., 2009), an ice giant is scattered inward by Saturn onto a Jupiter-crossing orbit, and then scattered outward by Jupiter. Saturn's semi-major axis is increased in the first gravitational encounter and Jupiter's reduced by the second, with the net result being an increase in their period ratio. While the trend is for the orbits of Jupiter and Saturn to diverge, depending on the geometry of the encounters, individual jumps of their semi-major axes can be either up or down (Nesvorný et al., 2013b).

In addition to numerous encounters with Jupiter and Saturn, the ice giant can encounter other ice giant(s) and in some cases cross significant parts of the asteroid belt (Roig & Nesvorný, 2015). The gravitational encounters occur over 10 000–100 000 years (Morbidelli et al., 2010), and end when dynamical friction with the planetesimal disk dampens its eccentricity, raising its perihelion beyond Saturn's orbit; or when the ice giant is ejected from the solar system (Nesvorný & Morbidelli, 2012). Resonant trapping of primordial objects may have originated in such a phase (Gaspar et al., 2017).

**Orbit of Mercury** The orbit of Mercury has large values of eccentricity and inclination (Figure 12.14) that are not easily explained if it formed on a circular and coplanar orbit. In the framework of the 'jumping Jupiter' model, some instability models can produce the observed values of its eccentricity and inclination, provided that relativistic effects are included in the perihelion precession (Roig et al., 2016). The orbital excitation is driven by the fast change of the normal oscillation modes of the system corresponding to the perihelion precession of Jupiter (for the eccentricity) and the nodal regression of Uranus (for the inclination).

**Late heavy bombardment** One of the consequences of the increasing eccentricities of the ice giants as Saturn crossed the 1:2 Jupiter resonance would have been the penetration of their orbits into the outer planetesimal disk, resulting in a brief phase of rapid and enhanced planetesimal scattering (Figure 12.20).

Gomes et al. (2005b) associated this event with the *Late Heavy Bombardment* (a period,  $\sim 4.1$ – $3.8$  Ga, in which many impact craters are believed to have formed on the Moon, and by inference also on Mercury, Venus, Earth, and Mars; see box, page 669). The lunar impact chronology then fixes the epoch of the inferred resonant crossing to  $\sim 700$  Myr after the solar system formation.

The Nice model predicts planetesimal numbers reaching the Moon consistent with the cratering record from the Late Heavy Bombardment (Gomes et al., 2005b; Morbidelli & Levison, 2008). Resulting impacts on Jupiter's moons are sufficient to trigger Ganymede's differentiation but not Callisto's (Barr & Canup, 2010). Jupiter's Trojan asteroids may have been captured at the same time (Morbidelli et al., 2005).

**Other related studies** The Nice model has been adopted as a reference for numerous related investigations. Its success in reproducing many, although not all, of the major features of the solar system lends further weight to the overall paradigm of planet formation according to the solar nebula hypothesis, and to the effects of planetesimal-driven migration. Studies include:

- the formation, accretion and migration history, chronology, and orbits of the giant planets, including: the migration of Neptune (Gomes et al., 2004); formation of the giant planets (Desch,

2007; Benvenuto et al., 2009); the outer solar system chronology (Johnson et al., 2008c); implied encounters between Saturn and Uranus or Neptune (Morbidelli et al., 2009b); the formation sequence of Jupiter and Saturn (Guilera et al., 2011); the formation location of Uranus and Neptune constrained by comets (Kavelaars et al., 2011); the accretion history of Uranus and Neptune (Li et al., 2011); accretion by Uranus and Neptune from planetary embryos (Izidoro et al., 2015a); excitation of the obliquities of Jupiter and Saturn during spin–orbit resonances (Vokrouhlický & Nesvorný, 2015); Neptune's migration history from the large-perihelion resonant population (Kaib & Shepard, 2016); Jupiter's core formation, and the absence of terrestrial planets, in the innermost solar system (Raymond et al., 2016); magnitude and timing of the instability (Toliou et al., 2016); and implications for the timing of the instability from disk clearing (Deienno et al., 2017).

- the formation of the terrestrial planets and accretion in the inner solar system, including: terrestrial planet formation (O'Brien et al., 2006; Brasser et al., 2009); accretion in the inner solar system (Raymond et al., 2009c); effects on terrestrial planet formation (Walsh & Morbidelli, 2011); constraints from secular resonances on the terrestrial planets (Agnor & Lin, 2012); constraints on the primordial orbits of the terrestrial planets (Brasser et al., 2013b); terrestrial planet formation during the 1:2 resonance crossing (Lykawka & Ito, 2013); accretion and differentiation of the terrestrial planets and implications for composition (Rubie et al., 2015); and the high eccentricity and inclination of Mercury's orbit (Roig et al., 2016).

- disk dependencies, including: dependency on disk surface density profile (Haghighipour & Winter, 2016); and effects of the self-gravity of the planetesimal disk (Fan & Batygin, 2017).

- the formation and resonances in the asteroid and Kuiper belts, including: formation of the Kuiper belt (Booth et al., 2009; Batygin & Brown, 2010); resonances in the formation of the Kirkwood gaps (Minton & Malhotra, 2009); the asteroid belt as a relic of a chaotic early solar system (Izidoro et al., 2016); the non-resonant Kuiper belt populations explained by Neptune's 'grainy' orbital migration (Nesvorný & Vokrouhlický, 2016b); the capture of trans-Neptunian planetesimals in the main asteroid belt (Vokrouhlický et al., 2016); the detailed orbital distribution of the Kuiper belt (Pike et al., 2017); and predictions for the detailed structure of high-perihelion trans-Neptunian objects (Pike & Lawler, 2017).

- the formation and resonant structure of the Trojan asteroids of Jupiter (Marzari & Scholl, 2007; Robutel & Bodossian, 2009); and Neptune (Lykawka et al., 2010).

- the delivery to the Earth of H<sub>2</sub>O (O'Brien et al., 2006); and other atmophile elements (Matsumura et al., 2016).

- other effects on outer solar system bodies, including: effects of the outer planets on primordial satellites (Deienno et al., 2011); limits on the encounters for the survival of Jupiter's Galilean satellites (Deienno et al., 2014); and the evolution of a Pluto-like system (Pires et al., 2015).

### 12.6.4 The Grand Tack model

Notwithstanding its successes, the limitations of the planetesimal-driven Nice model in reproducing certain features of the asteroid and Kuiper belt (e.g. Wolff et al., 2012; Brasser & Morbidelli, 2013), the continued existence of the outer planetary satellites (e.g. Nimmo & Ko-

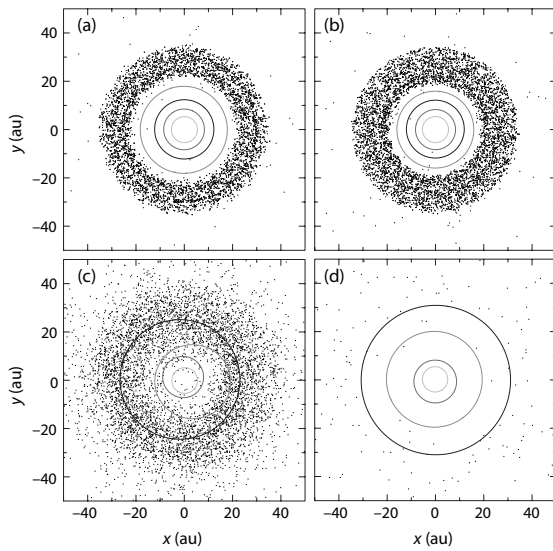


Figure 12.20: Numerical simulations of the Late Heavy Bombardment in the Nice model. Planet orbits and disk planetesimals are projected on the initial mean orbital plane. The four giant planets were initially on nearly circular co-planar orbits, with  $a = 5.45, 8.18, 11.5$  and  $14.2$  au, and the planetesimal disk, of mass  $35M_{\oplus}$ , extended from 15.5–34 au. Panels represent the system at (a) the start of planetary migration (100 Myr); (b) just before the start of the Late Heavy Bombardment (879 Myr); (c) just after its start (882 Myr); and (d) 200 Myr later when only 3% of the initial disk mass remains, and the planets have achieved their final orbits. From Gomes et al. (2005b, Figure 2), by permission from Nature/Springer/Macmillan Ltd, ©2005.

rycansky, 2012), and the anomalous mass of Mars, inspired the next advance in migration models.

The *Grand Tack* model (Walsh et al., 2011) addresses various features of the formation of the *inner* solar system, and specifically couples the gas-driven migration of giant planets to the accretion of the terrestrial planets. It invokes a two-stage, inward then outward, *gas-driven migration* of Jupiter and Saturn (Figure 12.21). The entire process, taking some 500–600 kyr, would have taken place in the first few Myr of the solar system, during or shortly after the formation of the giant planets, when gas was still present in the protoplanetary disk around the Sun. Accordingly, it would have preceded any subsequent Nice-type planetesimal migration phase.

The model rests on previous hydrodynamical simulations showing that the gas-driven migration of Jupiter can be split into two regimes (described further in the accompanying box, page 699): when Jupiter is the only giant planet in the disk, it migrates inwards. However, when paired with Saturn, both planets typically migrate outwards, locked in a 2:3 mean motion resonance. Assuming that Saturn formed later than Jupiter, Jupiter would have migrated inwards while Saturn was still growing; then, when Saturn reached a mass close to its current value, it started to migrate inwards more

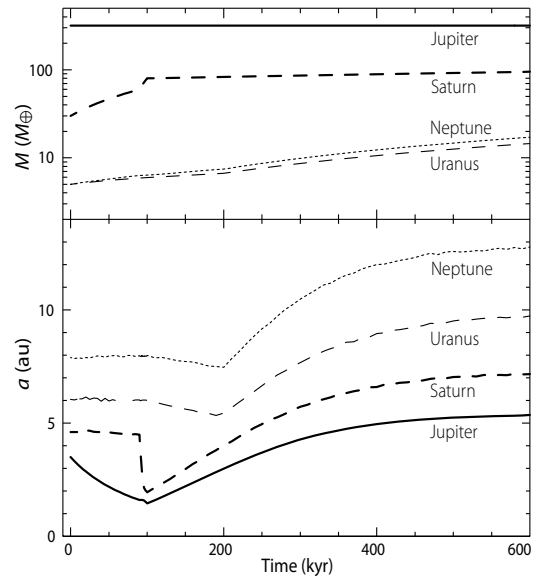


Figure 12.21: Evolution of the solar system giants according to the Grand Tack hypothesis, with parameters adopted by Walsh et al. (2011), showing their radial migration (top) and mass growth (bottom). From Walsh et al. (2011, Figure 1), by permission from Nature/Springer/Macmillan Ltd, ©2011.

rapidly than Jupiter, until it captured the latter in the 3:2 resonance. Thereafter, the two planets migrated outwards together until the disappearance of the gas disk.

The outcome of this process is a reduced surface density of solids beyond 1 au, leaving a small Mars and a dynamically excited, depleted asteroid belt.

The inward and outward migration is consistent with results from previous hydrodynamical simulations (e.g. Masset & Snellgrove, 2001; Morbidelli & Crida, 2007). The natural convergence of Jupiter and Saturn into the 3:2 resonance, and the subsequent gas-driven outward migration, has also been confirmed by various other studies (Pierens & Nelson, 2008a; Zhang & Zhou, 2010a,b; Pierens & Raymond, 2011; D'Angelo & Marzari, 2012), including under conditions of viscous heating and radiative cooling (Pierens et al., 2014).

Other features of the Grand Tack model have been variously discussed (e.g. Morbidelli et al., 2012a; Jacobson & Morbidelli, 2014), including a suggested ‘tack’ slightly further out at  $\sim 2$  au (Brasser et al., 2016).

In their review of the Grand Tack model, Raymond & Morbidelli (2014) consider that the most critical unknown is the timing and rate of gas accretion onto Saturn and Jupiter, the scenario requiring synchronisation between gas giant formation, the evolution and dispersal of the gas disk, and the growth of solids at 1–3 au.

**The mass of Mars** The anomalously low mass of Mars has long been a problem for models of solar system formation, which the Grand Tack model successfully resolves. It reproduces the mass–orbit distribution of the terrestrial planets, in-

**Details of the Grand Tack model:** In the model's initial configuration (Figure 12.21, and as described by Dones et al. 2015), Jupiter is fully formed, near the ice line at  $\sim 3.5$  au. After clearing a gap in the gas disk, it undergoes type II migration (§10.10.2), moving slowly toward the Sun over  $10^5$  yr. Uninterrupted, migration would leave it in a close orbit around the Sun, as in other hot Jupiters.

Saturn's  $30M_{\oplus}$  core is initially at 4.5 au, and grows to  $60M_{\oplus}$  as Jupiter migrates inward. Inward type I migration of planetary cores is inhibited in disks with a realistic cooling time scale (§10.10.2); thus Saturn's core remains at 4.5 au during this phase. Similarly, the cores of Uranus and Neptune begin at 6 and 8 au, and grow from  $5M_{\oplus}$ , without migrating. Once Saturn reaches  $60M_{\oplus}$  its inward migration begins (Kley & Crida, 2008), and is much faster than that of the fully grown Jupiter (Masset & Papaloizou, 2003).

Consequently, Saturn converges on Jupiter, and is eventually captured in a 3:2 mean motion resonance with it (Masset & Snellgrove, 2001). The model conditions ensure resonance trapping occurs when Jupiter is at 1.5 au.

An overlapping gap in the gas disk then forms around Jupiter and Saturn. If the gap was completely cleared, the larger mass of Jupiter would cause their positions to shift outward relative to the gap until the torques from the inner and outer disks were balanced, and the inward type II migration of both planets would continue (Morbidelli & Crida, 2007). The interaction between the planets, however, prevents Saturn from completely clearing its region of the disk (Brasser et al., 2016). This gas is able to stream across the gap from the outer disk to the inner disk, and exchanges angular momentum with the planets during its passage (Masset & Snellgrove, 2001). This allows the planets to reverse their migration, with Jupiter at 1.5 au, from where they migrate outwards together.

On their outward migration, they capture Uranus and Neptune in resonance, and these are also driven outwards. Saturn, Uranus and Neptune reach their full mass at the end of the migration with Jupiter at 5.4 au. The migration rate decreases exponentially as the gas disk dissipates. The final orbits of the giants are consistent with their current configuration when their later dynamical evolution is considered (Morbidelli et al., 2007; Batygin & Brown, 2010).

cluding that of Mars, as well as their orbital properties (see also Jacobson & Morbidelli, 2014). It essentially provides the conditions on the radial distribution of solid material which was identified in previous studies as a prerequisite for the low mass of Mars (§12.2.1): if the outer edge of the embryo and planetesimal disk is at  $\sim 1$  au, with no solid material beyond, such simulations consistently produce a small Mars.

The change in direction of migration, or 'tack', was explicitly set to occur when Jupiter was at 1.5 au, so that accretion from the post-sculpted inner disk of embryos could reproduce the mass distribution of the terrestrial planets, and in particular the large Earth/Mars ratio.

By generating a mass deficit close to the Sun, the outward migration of Jupiter's core may also explain the absence of terrestrial planets interior to Mercury, in contrast with those found by Kepler (Raymond et al., 2016).

**Re-population of the asteroid belt** A key feature of the Grand Tack model is the survival, via re-population, of the asteroid belt (Minton & Malhotra, 2011; Morbidelli et al., 2010; Batygin et al., 2011a; Jacobson & Morbidelli, 2014). Given that Jupiter

would have migrated through the asteroid belt region twice, inwards then outwards, it might be expected that the asteroid belt would now be largely empty. In contrast, simulations show that the region is depleted by the inward passage of the giant planets but, as Jupiter crosses the region for the second time, it is re-populated by a small fraction of the planetesimals scattered by the migrating giants (Walsh et al., 2011).

In particular, the inner asteroid belt is re-populated mainly by planetesimals that were originally inside the orbit on which Jupiter formed (i.e., inside  $\sim 3$  au), while the outer belt is re-populated mainly by planetesimals originally between and beyond the giant planet orbits. Assuming that Jupiter initially formed near the snow line, it is plausible to identify planetesimals originally closer to the Sun with the anhydrous E- and S-type asteroids, and those originally in between and beyond the giant planet orbits with the primitive C-type asteroids (Jacobson & Morbidelli, 2014).

With this assumption, the Grand Tack scenario can explain the co-existence of asteroids of very different physical properties in the main belt, and accordingly both the terrestrial planets and the asteroid belt within a single framework.

**Constraints on the Moon-forming impact** The giant impact phase follows the oligarchic growth phase, which builds a bimodal mass distribution within the disk of embryos and planetesimals. By varying the ratio of the total mass in the embryo population to the total mass in the planetesimal population and the mass of the individual embryos, Jacobson & Morbidelli (2014) explored how disk conditions control the final planets.

They found that the total mass ratio of embryos to planetesimals controls the timing of the last giant (Moon forming) impact and its violence, while the initial embryo mass sets the size of the lunar impactor and the growth rate of Mars. They concluded that, at the beginning of the giant impact phase, the protoplanetary disk had most of its mass in Mars-sized embryos, and only a small fraction in planetesimals. They inferred that the Moon-forming event occurred between 60–130 Myr after the formation of the first solids, and was caused most likely by an object with a mass similar to that of Mars, consistent with other constraints (§12.3.3).

**Water delivery to Earth** During the phase of outward planet migration, the scattering towards the inner solar system of primitive planetesimals originally located beyond Saturn, also helps to explain the delivery of  $H_2O$  to the terrestrial planets. In accreting some 1–2% of their total mass from these planetesimals, with an assumed 10%  $H_2O$  by mass, simulations show that they can deliver a total quantity comparable to that estimated on Earth today (O'Brien et al., 2014, see also §12.3.4).

**Transient heating** Migration of the giant planets through the asteroid belt creates a spike in impact velocities that could explain creation of the carbonaceous chondrites (box, page 683). Vaporisation of their metal nodules could occur at impacts  $\geq 18$   $km\ s^{-1}$ , well beyond the maximum of  $12\ km\ s^{-1}$  found in standard accretion models. However, in the Grand Tack model, Jupiter's migration results in a 0.5 Myr period of high impact velocities, perhaps reaching  $40\ km\ s^{-1}$ , sufficient to vaporise metals (Johnson et al., 2016b). If the formation of carbonaceous chondrites was due to Jupiter's migration, it would have occurred some 4.5–5 Myr after the formation of the solar system, itself suggesting that the formation of the giant planet cores was protracted, and that the solar nebula persisted for  $\sim 5$  Myr.

### 12.6.5 Gas and planetesimal migration

The final orbits of the giant planets in the Grand Tack model are consistent with the initial conditions of the most recent version of the Nice model (e.g. Levison et al., 2011; Nesvorný & Morbidelli, 2012) that explains the final transition towards the current giant planet orbits, hundreds of Myr after the disappearance of the gas disk.

In this way, the combination of the two, a 'Grand Tack' first modifying the inner solar system masses and orbits through gas migration, followed by a modified 'Nice model' adjusting the giant planet orbits through planetesimal migration, appears to explain many of the detailed properties of both major and minor constituents of the inner and outer solar system.

If these models prove to be correct, then the solar system had initially more of a bimodal structure, with Mars-mass planetary embryos inside the snow line and giant planet cores outside. In this case, the tri-modal structure, i.e. the depletion between 1 au and the orbit of Jupiter, was then generated by Jupiter's migration.

No complete migration model has been fully embraced as a description of the solar system formation. Associated investigations, including efforts to reconcile models of the solar system with more general population synthesis models (§10.13), are ongoing. Outstanding questions in understanding the solar system architecture are detailed by Morbidelli & Raymond (2016).



# Appendix A. Numerical quantities

Table A1 lists some key physical quantities and derived parameters at high levels of precision. Table A2 lists approximate values of some other relevant properties, for comparison with the emerging properties of exoplanets.

## The systems of standards

Beyond a small number of basic physical quantities (notably  $c$ ,  $G$ , and  $h$ ) the relevant system of astronomical units is essentially defined by four numbers (Klioner, 2008): the length of the day,  $d$ ; the mass of the Sun,  $M_\odot$  (in practice  $GM_\odot$ ); the astronomical unit,  $A_m$ ; and the Gaussian constant of gravitation,  $k$ . Since the First Edition published in 2011, (small) changes have been made to the definition of the astronomical unit (IAU 2012; see also Capitaine et al. 2012), to  $G$  and  $h$  (CODATA14, updating CODATA06), and to other solar system quantities through improved ephemerides (INPOP10e, replacing INPOP06).

Sources for the referenced standards include:

- CODATA14: recommended values from the CODATA Task Group on Fundamental Constants (Mohr et al., 2016); see also [www.codata.org](http://www.codata.org) and [physics.nist.gov/cuu/Constants](http://physics.nist.gov/cuu/Constants).
- IAU(2009): the IAU (2009) system of astronomical constants (Luzum et al., 2011). The compilation of *defining constants*, fixed by convention, and other *current best estimates*, are listed at [maia.usno.navy.mil/NSFA](http://maia.usno.navy.mil/NSFA).
- INPOP10e: self-consistent (TCB-compatible) solar system quantities from the planetary ephemeris developed at the IMCCE–Observatoire de Paris (Fienga et al., 2013a,b). INPOP provides an alternative to the JPL DE405 and DE414 (Konopliv et al., 2006). The latest INPOP13 values (Fienga et al., 2015) have not been included.

## Notes to Table A1

- (1) the astronomical unit was re-defined by the IAU in 2012, consistent with the value adopted in 2009 (Luzum et al., 2011).
- (2) this value, from CODATA14, in principle supersedes that previously adopted by the IAU (2009).
- (3) this is derived from other defining quantities. CODATA14 gives a (similar) measured value  $5.670367(13) \times 10^{-8}$ .
- (4) because of the limited accuracy in the knowledge of  $G$ , planetary ephemerides, and associated masses and linear dimensions, are still calculated in terms of the Gaussian constant of gravitation,  $k = 4\pi^2 A_m^3 / (P_\oplus^2 (M_\odot + M_\oplus))$ . Gauss (1857) used a numerical value of  $k$  which continues to be used to define the relation between the au and  $GM_\odot$  in the IAU (2009) system, although  $GM_\odot$  can now be estimated directly from modern planetary ephemerides (including INPOP10e).
- (5) the Julian Year is an IAU definition, entering directly in the definition of the unit of proper motion,  $\text{mas yr}^{-1}$ .

(6) in high-accuracy work (e.g. Gaia astrometry), care is needed in representing quantities dependent on  $\pi$  due to rounding. Double-precision floating-point numbers following IEEE standards have 64 bits (16 significant digits) yielding:

- $\pi = 3.141\,592\,653\,589\,793\,238$
  - $1 \text{ degree} \equiv \pi/180 = 1.745\,329\,251\,994\,33 \times 10^{-2} \text{ rad}$
  - $1 \text{ mas} \equiv \pi/(180 \times 3600 \times 1000) = 4.848\,136\,811\,095\,36 \times 10^{-9} \text{ rad}$
- (7)  $\gamma = 1$  is fixed in INPOP10e (see also Fienga et al., 2015). Other terms given here can be derived numerically, e.g., Klioner (2003).  $\alpha_{\text{pN}}(\perp)$  is the post-Newtonian deflection angle for an observer at 1 au from the Sun, of a light ray arriving orthogonal to the solar direction due to the spherically symmetric part of the Sun's gravitational field.  $\alpha_{\text{pN}}(R_\odot)$  is the post-Newtonian deflection angle for an observer at 1 au from the Sun, of a similar solar-limb grazing light ray.

(8) accurate barycentric arrival times require correction both for geometrical (Rømer) delay associated with the observer's motion around the barycentre, and relativistic (Shapiro) delay caused by the gravitational bodies in the solar system; see, e.g., Lindgren & Dravins (2003, Section 4.3), and Will (2003, eqn 7).

(9) although  $M_\odot$  is considered as a constant, the physical mass of the Sun decreases at  $\sim 10^{-13} M_\odot \text{ yr}^{-1}$  carried by solar radiation (Krasinsky & Brumberg, 2004). Secular acceleration in the mean longitudes of the inner planets currently places a limit of  $\dot{G}/G = -2 \pm 5 \times 10^{-14} \text{ yr}^{-1}$  (Pitjeva, 2005), equivalent to the same limit on the determination of  $\dot{M}/M$  (Klioner, 2008).

(10)  $R_\odot$  is from Haberreiter et al. (2008, Table 3), from which  $\theta_\odot$  is derived via  $A_m$ . A similar value of  $\theta_\odot$  was measured by Chollet & Sinceac (1999). At this accuracy, oblateness is irrelevant.

(11) INPOP13c gives  $J_{2,\odot} = 2.20 \pm 0.15$ , consistent with accurate values from helioseismology (Fienga et al., 2015, their Table 8).

(12) see Perryman (2009, Section 7.2.1).

(13) see Mamajek et al. (2015b).

(14) Grevesse & Noels (1993) give  $Y_\odot$  and  $Z_\odot$ , from which  $X_\odot = 1 - Y_\odot - Z_\odot$ . Associated parameters relevant for the equation of state are the mean molecular weight  $\mu_\odot = 1/(2X_\odot + 3Y_\odot/4 + Z_\odot/2) = 0.6092$  and the mean molecular weight per free electron  $\mu_{e,\odot} = 2/(X_\odot + 1) = 1.1651$ . These derivations assume complete ionisation, and that metals give  $\sim 0.5$  particles per  $m_{\text{H}}$  (e.g. Karttunen, 1987, Section 11.2).

(15) here, 'Earth' includes the Earth's atmosphere, but excludes the Moon. 'Earth-system' includes the Moon. Similarly, the 'Jupiter-system' includes the contribution from its moons.

(16) the *de facto* standard Jupiter radius for exoplanet work (IAU 2015); see further details in Section 1.4.

(17) mean value at J2000.0 from a 250-year fit to JPL DE200. The orbital period is derived from mean longitude rates.

(18) Cox (2000, Sect 12.1); cf. Pitjeva (2003); Fienga et al. (2013b)

Table A1: Fundamental and derived quantities, and associated reference values.

Symbol	Meaning	Source/Derivation	Value
Physical constants:			
$c$	Speed of light in vacuum (exact)	CODATA14	$2.997\,924\,58 \times 10^8 \text{ m s}^{-1}$
$A_m$	Astronomical unit (in m) <sup>1</sup>	IAU (2009, 2012)	$1.495\,978\,707\,000 \times 10^{11} \text{ m}$
$G$	Newton's constant of gravitation <sup>2</sup>	CODATA14	$6.674\,08(31) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$
$h$	Planck constant	CODATA14	$6.626\,070\,040(81) \times 10^{-34} \text{ J s}$
$\sigma$	Stefan–Boltzmann constant <sup>3</sup>	$2\pi^5 k^4 / (15c^2 h^3)$	$5.670\,367 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
$k$	Gaussian gravitational constant (exact) <sup>4</sup>	IAU (2009)	$0.017\,202\,098\,95 \text{ au}^{3/2} \text{ day}^{-1} M_\odot^{-1/2}$
Time scales:			
$d$	Day in s (any time scale)		86400 (exactly)
$y$	Julian Year in days <sup>5</sup>		365.25 (= 31 557 600 s)
J2000	Julian date of standard epoch, J2000.0 <sup>5</sup>		2451 545.0 JD
Derived quantities <sup>6</sup> :			
$A_V$	Proper motion constant	$A_m / (y \times d \times 1000)$	$4.740\,470\,464 \text{ km yr s}^{-1}$
pc <sub>m</sub>	Parsec in m	$A_m \times 180 \times 3600 / \pi$	$3.085\,677\,581 \times 10^{16} \text{ m}$
pc <sub>au</sub>	Parsec in au	$180 \times 3600 / \pi$	$2.062\,648\,06 \times 10^5 \text{ au}$
ly <sub>m</sub>	Light year in m	$y \times d \times c$	$9.460\,730\,473 \times 10^{15} \text{ m}$
ly <sub>au</sub>	Light year in au	$y \times d \times c / A_m$	$6.324\,107\,708 \times 10^4 \text{ au}$
ly <sub>pc</sub>	Light year in pc	$y \times d \times c / \text{pc}_m$	0.306 601 pc
General Relativity:			
$\gamma$	General relativistic PPN parameter <sup>7</sup>	assumed (e.g. Will, 2006)	1
$\alpha_{\text{pN}(\perp)}$	Deflection angle at 1 au perp to ecliptic <sup>7</sup>	Klioner (2003)	$4.072 \times 10^{-3} \text{ arcsec}$
$\alpha_{\text{pN}(R_\odot)}$	Deflection angle at 1 au at solar limb <sup>7</sup>	Klioner (2003)	1.751 293 arcsec
$\Delta$	Shapiro time-delay constant <sup>8</sup>	$(1 + \gamma)(GM_\odot) / c^3$	$9.851 \times 10^{-6} \text{ s}$
Sun:			
$GM_\odot$	Heliocentric gravitational constant <sup>9</sup>	INPOP10e	$1.327\,124\,421\,08 \times 10^{20} \text{ m}^3 \text{ s}^{-2}$
$M_\odot$	Mass <sup>9</sup>	$(GM_\odot) / G$	$1.988\,48 \times 10^{30} \text{ kg}$
$R_\odot$	Radius in m <sup>10</sup>	Haberreiter et al. (2008)	$6.956\,580 \times 10^8 \text{ m}$
$\theta_\odot$	Apparent radius in arcsec <sup>10</sup>	$R_\odot \times 3600 \times 180 / (A_m \times \pi)$	959.17 arcsec
$\rho_\odot$	Mean mass density	$M_\odot / ((4/3)\pi R_\odot^3)$	$1.410 \text{ Mg m}^{-3}$
$g_\odot$	Surface gravity	$(GM_\odot) / R_\odot^2$	$274.2 \text{ m s}^{-2}$
$J_{2,\odot}$	Quadrupole moment <sup>11</sup>	INPOP10e	$1.80(25) \times 10^{-7}$
$M_{V,\odot}$	Johnson absolute $V$ magnitude <sup>12</sup>	Cayrel de Strobel (1996)	+4.83 mag
$M_{\text{bol},\odot}$	Bolometric magnitude <sup>12</sup>	Cayrel de Strobel (1996)	+4.75 mag
$BC_{V,\odot}$	Bolometric correction, Johnson $V$ band <sup>12</sup>	Cayrel de Strobel (1996)	−0.08 mag
$J_\odot$	Energy flux at 1 au <sup>13</sup>	Mamajek et al. (2015b)	$1361 \text{ W m}^{-2}$
$L_\odot$	Luminosity <sup>13</sup>	$4\pi A_m^2 J_\odot$	$3.8275 \times 10^{26} \text{ W}$
$T_{\text{eff},\odot}$	Effective (black-body) temperature <sup>13</sup>	$(L_\odot / 4\pi\sigma R_\odot^2)^{1/4}$	5772 K
$X_\odot, Y_\odot, Z_\odot$	H, He, and metal abundances by mass <sup>14</sup>	Grevesse & Noels (1993)	0.716 6, 0.265 9, 0.017 5
$\alpha_{\text{MLT},\odot}$	Mixing-length parameter	Girardi et al. (2000)	1.68
Earth-related:			
$GM_\oplus$	Geocentric gravitational constant <sup>15</sup>	INPOP10e	$3.986\,004\,418 \times 10^{14} \text{ m}^3 \text{ s}^{-2}$
$M_\oplus$	Earth mass <sup>15</sup>	$(GM_\oplus) / G$	$5.972\,37 \times 10^{24} \text{ kg}$
$M_\odot / M_\oplus$	Sun/Earth mass ratio <sup>15</sup>	INPOP10e	$3.329\,460\,487\,01 \times 10^5$
	Sun/Earth-system mass ratio <sup>15</sup>	INPOP10e	$3.289\,005\,596\,16 \times 10^5$
Jupiter-related:			
$M_\odot / M_J$	Sun/Jupiter-system mass ratio <sup>15</sup>	IAU (2009)	1047.348 644
$M_J$	Jupiter-system mass <sup>15</sup>	$M_\odot / (M_\odot / M_J)$	$1.898\,58 \times 10^{27} \text{ kg} \sim 9.5 \times 10^{-4} M_\odot$
$R_J$	Jupiter equatorial radius at $10^5 \text{ Pa}$ (1 bar) <sup>16</sup>	Mamajek et al. (2015b)	$7.1492 \times 10^7 \text{ m}$
$a_J$	Orbital semi-major axis of Jupiter-system <sup>17</sup>	Seidelmann (1992)	5.203 au
$P_J$	Jupiter sidereal orbital period <sup>17</sup>	Seidelmann (1992)	11.862 615 yr
Solar system mass composition <sup>18</sup> :			
	Total mass of planets		$446.6 M_\oplus$
	Total mass of satellites		$0.104 M_\oplus$
	Total mass of asteroids		$0.000\,30 M_\oplus$
	Total mass of meteors and comets		$10^{-9} M_\oplus$
	Total mass of planetary system		$0.001\,34 M_\odot$
	Total angular momentum of planetary system		$3.148 \times 10^{43} \text{ kg m}^2 \text{ s}^{-1}$
Local Galactic constants:			
$A$	Oort constant, $A$	Feast & Whitelock (1997)	$+14.82 \text{ km s}^{-1} \text{ kpc}^{-1}$
$B$	Oort constant, $B$	Feast & Whitelock (1997)	$-12.37 \text{ km s}^{-1} \text{ kpc}^{-1}$
$\Omega_0$	Angular velocity	$A - B$	$+27.19 \text{ km s}^{-1} \text{ kpc}^{-1}$
$R_0$	Galactocentric radius of the Sun	Malkin (2012)	$8.0 \pm 0.25 \text{ kpc}$
$V_0$	Circular velocity at $R_0$	$R_0 \Omega_0$	$218 \text{ km s}^{-1}$
$P_{\text{rot}}$	Galactic rotation period	$(2\pi / \Omega_0)(\text{pc}_m / y \times d)$	$2.26 \times 10^8 \text{ yr}$
$\kappa_0$	Epicycle frequency	$(-4B(A - B))^{0.5}$	$36.7 \text{ km s}^{-1} \text{ kpc}^{-1}$
$Z_0$	Sun's height from Galactic mid-plane	Perryman (2009, Section 9.2.2)	+20 pc
$\rho_0$	Oort limit (disk+dark halo)	Holmberg & Flynn (2000)	$0.102 M_\odot \text{ pc}^{-3}$
$P_\perp$	Vertical oscillation period	$(\pi / G\rho_0)^{0.5} \text{ s} (\rho_0 \text{ in SI})$	$8.2 \times 10^7 \text{ yr}$

Table A2: Properties of the solar system planets.

Property	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
<b>Orbit:</b>								
semi-major axis, $a$ ( $10^6$ km)	58	108	150	228	778	1427	2871	4498
" (au)	0.39	0.72	1.00	1.52	5.20	9.54	19.19	30.07
sidereal period (Julian years)	0.24	0.62	1.00	1.88	11.86	29.42	83.75	163.72
sidereal rotation period (d)	58.646	-243.019	0.997	1.026	0.410	0.426	-0.718	0.671
eccentricity, $e$	0.206	0.007	0.017	0.093	0.048	0.054	0.047	0.009
inclination to ecliptic, $i$ ( $^\circ$ )	7.0	3.4	0.0	1.9	1.3	2.5	0.8	1.8
obliquity ( $^\circ$ )	0.0	177.3	23.4	25.2	3.1	26.7	97.9	29.6
<b>Physical properties:</b>								
equatorial radius, $R_{\text{eq}}$ (km)	2 440	6 052	6 378	3 397	71 492	60 268	25 559	24 764
" $R_{\text{eq}}/R_{\oplus}$	0.38	0.95	1	0.53	11.21	9.45	4.00	3.88
volume, $V/V_{\oplus}$	0.05	0.88	1	0.15	1316	755	52	44
mass, $M$ ( $10^{24}$ kg)	0.33	4.87	5.97	0.64	1898.70	568.51	86.85	102.44
" $M/M_{\oplus}$	0.06	0.81	1	0.11	317.82	95.16	14.54	17.15
" $M/M_{\text{J}}$	0.0002	0.0026	0.0031	0.0003	1	0.2994	0.0457	0.0540
" $M/M_{\odot}$	$1.66 \times 10^{-7}$	$2.45 \times 10^{-6}$	$3.00 \times 10^{-6}$	$3.23 \times 10^{-7}$	$9.55 \times 10^{-4}$	$2.86 \times 10^{-4}$	$4.37 \times 10^{-5}$	$5.15 \times 10^{-5}$
density, $\rho$ ( $\text{Mg m}^{-3}$ )	5.43	5.24	5.52	3.94	1.33	0.70	1.30	1.76
surface gravity, $g$ ( $\text{m s}^{-2}$ )	3.70	8.87	9.80	3.71	23.12	8.96	8.69	11.00
escape velocity ( $\text{km s}^{-1}$ )	4.2	10.4	11.2	5.0	59.5	35.5	21.3	23.7
oblateness, $(R_{\text{eq}} - R_{\text{pol}})/R_{\text{pol}}$	0.0001	0.0001	0.0035	0.0052	0.0649	0.0980	0.0229	0.0171
quadrupole moment, $J_2$	0.0001	0.0000	0.0011	0.0020	0.0147	0.0163	0.0033	0.0034
magnetic moment ( $\text{T m}^3$ )	$5.08 \times 10^{12}$	$< 6.65 \times 10^{12}$	$8.04 \times 10^{15}$	$< 2.35 \times 10^{12}$	$1.57 \times 10^{20}$	$4.60 \times 10^{18}$	$3.81 \times 10^{17}$	$2.02 \times 10^{17}$
dipole tilt ( $^\circ$ )	$< 10$	-	11.5	-	9.6	0.8	58.6	47.0
Satellites	0	0	1	2	67	$> 62$	27	14
<b>Astrometric effects on the Sun:</b>								
$a_{\odot}$ due to planet ( $\text{km}$ ) <sup>1</sup>	10	264	451	74	742903	407998	125399	231732
$\alpha_{\odot}$ at 10 pc ( $\mu\text{as}$ ) <sup>2</sup>	0.006	0.177	0.301	0.049	497	273	84	155
<b>Surface properties:</b>								
visibility: solid/cloud	s	c	s/c	s	c	c	c	c
visual geometric albedo	0.11	0.65	0.37	0.15	0.52	0.47	0.51	0.41
Bond albedo, $A_{\text{B}}$	0.12	0.75	0.31	0.25	0.34	0.34	0.30	0.29
effective temperature (K)	-	$\sim 230$	$\sim 255$	$\sim 212$	124	95	59	59
mean temperature (K)	440	730	288-293	183-268	-	-	-	-
scale height, $H$ (km)	-	15	8	11	19-25	35-50	22-29	18-22
<b>Atmospheric composition:</b>								
N <sub>2</sub>	-	0.035	0.781	0.027	-	-	-	-
O <sub>2</sub>	-	-	0.209	$1.3 \times 10^{-3}$	-	-	-	-
CO <sub>2</sub>	-	0.965	$3.3 \times 10^{-4}$	0.953	-	$< 3 \times 10^{-10}$	$< 3 \times 10^{-10}$	$< 5 \times 10^{-10}$
CO	-	$3 \times 10^{-7}$	$2 \times 10^{-7}$	$2.7 \times 10^{-3}$	$1 \times 10^{-10}$	$1 - 3 \times 10^{-9}$	$< 5 \times 10^{-7}$	$6 \times 10^{-7}$
CH <sub>4</sub>	-	-	$2.0 \times 10^{-6}$	-	$2.4 \times 10^{-3}$	$1 - 4 \times 10^{-3}$	$< 0.02$	$< 0.02$
NH <sub>3</sub>	-	-	$4 \times 10^{-9}$	-	$< 7 \times 10^{-4}$	$< 1 \times 10^{-4}$	$< 1 \times 10^{-4}$	-
H <sub>2</sub> O	-	$2 \times 10^{-5}$	$1 \times 10^{-6}$	$3 \times 10^{-4}$	$< 6 \times 10^{-5}$	$2 \times 10^{-7}$	$< 0.5 \times 10^{-8}$	$< 2 \times 10^{-9}$
H <sub>2</sub>	-	-	$5 \times 10^{-7}$	-	0.863	0.94	0.85	0.85
He	-	$1.2 \times 10^{-5}$	$5.2 \times 10^{-6}$	-	0.156	0.06	0.15	0.15

**Notes to Table A2**

This is a (generally low-precision) summary of some relevant properties of the solar system planets. Values are mostly from Cox (2000, Tables 12.1–12.10), supplemented by oblateness and quadrupole moment from Lang (1992) and Yoder (1995), atmospheric composition from Encrenaz et al. (2004), Bond albedos from Cole & Woolfson (2002, Topic X), and magnetic moment and dipole tilt from Lang (1992). See also [nssdc.gsfc.nasa.gov/planetary/factsheet](https://nssdc.gsfc.nasa.gov/planetary/factsheet).

Various other values can be found in the literature, including more precise planet masses as adopted by the IAU (2009), or as derived from INPOP10e (Fienga et al., 2013b).

(1) orbital semi-major axis of a  $1M_{\odot}$  star due to a planet with the same  $M_{\text{p}}$  and  $a_{\text{p}}$ , i.e.  $a_{\odot} = a_{\text{p}} \times (M_{\text{p}}/M_{\odot})$ .

(2) associated astrometric signature for a  $1M_{\odot}$  star at 10 pc, i.e.  $\alpha_{\odot}$  (arcsec) =  $(a(\text{au})/10) \times (M_{\text{p}}/M_{\odot})$ .



# Appendix B. Notation and acronyms

## Notation

When followed by a chapter number in braces [...], the notation is generally used only within that chapter.

$\oplus$	Earth (subscript)	$c_s$	sound speed [6,10]
$\odot$	Sun (subscript)	$C_d$	drag coefficient [10]
$\star$	star (subscript)	$C_n^2(h)$	atmospheric structure function [3]
$a$	semi-major axis	$d$	angular star–planet separation, in units of $\theta_E$ [5]
$a$	dust particle radius [10]	$d$	projected star–planet separation [6]
$a$	activity coefficient (thermodynamic) [11]	$d, d_\star$	star distance
$a''$	semi-major axis in angular measure [2]	$d(t)$	velocity trend parameter [2]
$a_p$	semi-major axis of planet around star [2]	$D$	telescope diameter
$a_\star$	semi-major axis of star around barycentre [2]	$D$	object diameter [10]
$a_s$	planetary satellite orbital radius [6]	$D_{\text{ecl}}$	secondary eclipse depth [6]
$A$	astronomical unit [2]	$D_L$	lens distance [5]
$A$	microlensing magnification (total) [5]	$D_{LS}$	lens–source distance [5]
$A_\pm$	microlensing image magnifications [5]	$D_S$	source distance [5]
$A_B$	Bond albedo	$\Delta$	photocentre displacement due to star spots [3]
$\mathbf{A}_G$	transformation matrix: Galactic system/ICRS [8]	$\Delta_i$	mutual orbit inclination
$A_m$	astronomical unit (in m) [6]	$\Delta F$	flux decrement during transit [6]
$A_p, A_v$	astronomical unit [8]	$e$	eccentricity (orbit)
$A_{\text{beam}}$	amplitude modulation of Doppler beaming [6]	$E$	telescope étendue [6]
$A_{\text{ellip}}$	amplitude modulation of ellipsoidal effect [6]	$E(t)$	eccentric anomaly [2]
$A_{\text{refl}}$	amplitude modulation of reflected light [6]	$\epsilon$	planet/star flux ratio [6]
$A-C, F-H$	Thiele–Innes constants [3]	$\epsilon$	tidal amplitude parameter [10]
$\alpha$	astrometric signature [3]	$\dot{\epsilon}$	internal energy source [11]
$\alpha$	source trajectory relative to star–planet axis [5]	$\eta$	compression ratio [11]
$\alpha$	differential rotation parameter [8]	$\eta_\oplus$	fraction of stars having Earth-like planets [11]
$\alpha$	exponent of power-law mass function [9]	$f$	atmospheric circulation parameter [6]
$\alpha$	turbulent efficiency in $\alpha$ -disks [10]	$f$	fugacity (thermodynamic) [11]
$\alpha_E$	microlensing deflection angle at $R_E$ [5]	$f_p$	planet flux [7]
$\alpha_{GR}$	gravitational deflection angle [5]	$f_\star$	star flux [7]
$\alpha_G, \delta_G$	north Galactic pole (ICRS) [8]	$f_+$	equatorial prolateness (tidal) [10]
$\alpha_{IR}$	spectral index in infrared [10]	$f_-$	polar flattening (tidal) [10]
$\alpha_{pN}$	post-Newtonian deflection angle [3]	$F_g$	gravitational scattering enhancement [10]
$b$	semi-minor axis [2]	$F_\odot$	solar flux [11]
$b$	impact parameter (light deflection) [5]	$F_{\text{EUUV}}$	extreme ultraviolet flux [11]
$b$	impact parameter (transit) [6]	$F_{\text{IR}}$	incident radiation flux [11]
$b$	Galactic latitude [8]	$F_{\text{rg}}$	runaway greenhouse flux [11]
$\mathbf{b}$	star position wrt solar system barycentre [8]	$g$	phase function [6]
$\mathcal{B}$	blended flux [6]	$g$	stellar surface gravity [3]
$B$	interferometer baseline [3]	$g_p$	planet surface gravity [6]
$B$	magnetic field strength [8]	$G$	gravitation constant
$BC$	bolometric correction [8]	$\gamma$	systemic radial velocity [2]
$c$	speed of light	$\gamma$	curvature per unit mass (ppN) [3]
$C$	angular momentum deficit [10]	$\gamma$	radial exponent of disk surface density [10]
$\mathcal{C}$	spectral line contrast [2]	$\Gamma$	gamma function [6]
$c, h, v_0$	linearised parameters for orbit fitting [2]	$\Gamma$	microlensing event rate [5]
		$h$	height of turbulent layers in atmosphere [3]
		$h$	disk height [10]
		$h$	Planck constant



$R_p$	planet radius	$\tau$	microlensing optical depth [5]
$R'_p$	planet radius (scaled) [11]	$\tau$	ingress and/or egress durations [6]
$R_{\text{eq}}, R_{\text{pol}}$	equatorial/polar radii [6]	$\tau$	stellar age [9]
$\bar{R}$	mean radius [12]	$\tau_a$	e-folding time, semi-major axis migration [2]
$R_R$	Roche radius (or Roche limit) [6]	$\tau_a$	time scale for tidal infall [10]
$R_S$	Schwarzschild radius [5]	$\tau_e$	e-folding time, eccentricity migration [2]
$R_J$	Jupiter radius	$\tau_c$	disk cooling time [10]
$R_\star$	stellar radius	$\tau_f$	disk friction time (viscosity) [10]
$R_\oplus$	Earth radius	$\tau_p$	amplitude of light travel time from primary [4]
$R_\odot$	solar radius	$\tau_{\text{syn}}$	time scale for tidal despin [10]
$R_{\text{spot}}$	star spot radius [6]	$\theta$	true longitude [2]
$\rho$	angular diameter of source star, in units of $\theta_E$ [5]	$\theta$	angular separation for reference/target star [3]
$\rho$	density	$\theta_E$	Einstein radius (angular) [5]
$\rho_s$	density of dust aggregates [10]	$\theta_I$	angle between lens and microlensed image [5]
$S$	stellar photon count rate [6]	$\delta\theta$	astrometric deflection of microlens image centroid [5]
$S$	Strehl ratio [7]	$\Delta\theta$	angular separation between microlens images [5]
$S$	solar constant [11]	$\theta_\pm$	angular positions of a pair of microlensed images [5]
$S$	entropy (per unit mass) [11]	$\theta_S$	angle between lens and source [5]
Stk	Stokes number [10]	$\theta_\star$	angular diameter of source star [5]
$\sigma$	standard error	$\Theta$	Safronov number [6]
$\sigma$	tidal dissipation constant per unit mass [10]	$u$	angular lens–source separation, in units of $\theta_E$ [8]
$\sigma'_{rv}$	radial velocity jitter [2]	$u_f$	fragmentation threshold velocity [10]
$\sigma_\delta$	relative angular positional error [3]	$v$	dust particle velocity [10]
$\sigma_{\text{ph}}$	photon-noise limited positional error [3]	$v_{\text{esc}}$	escape velocity at atmosphere exobase [11]
$\sigma_\psi$	single measurement error [3]	$v_r$	radial velocity
$\Sigma$	disk surface density [10]	$v_t$	transverse velocity [3]
$\Sigma_{\text{dust}}$	disk surface density in dust [10]	$v_\perp$	transverse velocity between source and lens [5]
$\Sigma_{\text{gas}}$	disk surface density in gas [10]	$v_\phi$	azimuthal velocity (within disk) [10]
$\Sigma_p$	disk surface density in planetesimals [10]	$v \sin i$	stellar rotation velocity
$t$	integration time [3]	$\mathbf{v}$	barycentric space velocity [8]
$t_0$	central microlensing event time [5]	$V$	interferometric visibility function [6]
$t_{0.5}$	radionuclide half-life [10]	$V$	visual magnitude
$t_E$	Einstein radius crossing time [5]	$V(h)$	wind velocity as a function of atmospheric height [3]
$t_F$	duration of flat part of transit [6]	$V_k$	Keplerian velocity (within disk) [10]
$t_{\text{ff}}$	gravitational free-fall time [10]	$V_w$	solar/stellar wind speed [8]
$t_p$	time of specified pericentre passage	$w(x_0)$	gravitational potential of solar system at $x_0$ [3]
$t_T$	total transit duration [6]	$XY$	rectangular coordinates in the orbit plane [3]
$T$	temperature	$z$	coordinate along line-of-sight [2]
$T_{\text{crit}}$	critical temperature [11]	$z$	complex eccentricity [6]
$T_{\text{eff}}$	effective temperature [8]	$z$	altitude (atmosphere) [11]
$T_{\text{eq}}$	planet equilibrium surface temperature [6]	$Z$	atomic number [11]
$T_p$	planet temperature [4]		
$T_{\text{tp}}$	triple point [11]		
$T_{\text{BB}}$	black body temperature [11]		

## Acronyms

Acronyms have been avoided to the extent considered reasonable. Some of the following do not appear in this treatment, but do appear in the associated literature.

AAT	Anglo–Australian Telescope	CARMENES	Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-IR and optical Echelle Spectrographs
ACS	Advanced Camera for Surveys (HST)	CAT	Coudé Auxiliary Telescope (ESO)
ADI	Angular Differential Imaging	CATS	Compound Arctic Telescope Survey
ADIPLS	Aarhus adiabatic oscillation package (asteroseismology)	CCD	charge-coupled device
ADONIS	Adaptive Optics Near Infrared System (ESO)	CD	Córdoba Durchmusterung
ADS	Astrophysics Data System (NASA archive)	CD–HPF	Cobb–Douglas Habitability Production Function
AFOE	Advanced Fiber Optic Echelle (Whipple Observatory)	CDA	CoRoT detrending algorithm
AFTA	Astrophysics Focused Telescope Assets (WFIRST)	CDFS	Chandra Deep Field–South
AGCM	atmospheric GCM	CDMS	Cologne Database for Molecular Spectroscopy
AGPM	annular groove phase mask (coronagraphy)	CDS	Centre de Données astronomiques de Strasbourg (Strasbourg astronomical data centre)
AIC	achromatic interferometric coronagraph	CE	Christian Era (aka AD)
AKARI	Japanese infrared satellite (ASTRO–F)	CELESTA	Catalogue of Earth–Like Exoplanet Survey Targets
ALMA	Atacama Large Millimeter Array	CES	Coudé Echelle Spectrometer (ESO)
AMD	angular momentum deficit	CFB	Continental Flood Basalts
AMEX	Astrometric Mapping Explorer (USNO)	CFBDS	Canada–France Brown Dwarf Survey
ANEOS	analytic equation of state (Sandia)	CFC	chlorofluorocarbons
ANU	Australian National University	CFHT	Canada–France–Hawaii Telescope
AO	adaptive optics	CHARA	Center for High Angular Resolution Astronomy
AOGCM	atmospheric–ocean GCM	CHARIS	Coronagraphic High Angular Resolution Imaging Spectrograph (Subaru)
APD	avalanche photodiode	CHEOPS	CHaracterising EXOPlanets Satellite
APEX	Atacama Pathfinder Experiment	CHIMERA	transmission spectroscopy retrieval routine
APF	Automated Planet Finder (Lick Observatory)	CHIRON	high-resolution spectrometer (CTIO)
APKC	Achromatic phase knife coronagraph	CIPM	International Committee for Weights and Measures (Comité International des Poids et Mesures)
APLC	Apodised pupil Lyot coronagraph	CLIMAP	Climate: Long range Investigation, Mapping, and Prediction
APO	Apache Point Observatory	CME	coronal mass ejection
APOGEE	APO Galactic Evolution Experiment (SDSS)	CMF	core mass fraction (structural models)
APOSTLE	Apache Point Survey of Transit Light curves of Exoplanets	CMOS	complementary metal–oxide–semiconductor
APT	Automatic Photoelectric Telescope (Fairborn)	CNES	Centre National d’Etudes Spatiales
ARC	Achromatic rotation–shearing coronagraph	CNS	Catalogue of Nearby Stars
ARENA	Antarctic Research, a European Network for Astrophysics	COBE	Cosmic Background Explorer
ARGOS	Advanced Rayleigh Guided Ground Layer AO System (LBT)	CODEX	COSmic Dynamics EXperiment
ARIEL	Atmospheric Remote–sensing Exoplanet Large–survey	CONICA	Coudé Near Infrared Camera (ESO)
ARIES	Arizona Infrared imager and Echelle Spectrograph (MMT)	COS	Cosmic Origins Spectrograph (HST)
AROME	Analytical Rossiter–McLaughlin effects	CPAIC	common–path achromatic interferometer–coronagraph
ASAS	All Sky Automated Survey	CPD	Cape Durchmusterung
ASAS–SN	All Sky Automated Survey for SuperNovae	CRIRES	Cryogenic high–resolution InfraRed Echelle Spectrograph (ESO)
ASCA	Advanced Satellite for Cosmology and Astrophysics	CSHELL	Cryogenic Near–IR Facility Spectrograph (IRTF)
ASKAP	Australian SKA Pathfinder	CSTAR	Chinese Small Telescope ARray (Dome A)
ASTEP	Antarctic Search for Transiting Extrasolar Planets	CTA	Cherenkov Telescope Array
ASTRA	ASTrometric and phase–Referenced Astronomy (Keck–I)	CTIO	Cerro Tololo Inter–American Observatory
ATA	Allen Telescope Array	CUDA	a parallel computing platform model
ATLAS	stellar atmosphere modeling code	CUTE	Colorado Ultraviolet Transit Experiment
ATST	Advanced Technology Solar Telescope, now DKIST	CV	cataclysmic variable
BART	Bayesian Atmospheric Radiative Transfer fitting code	DAO	Dominion Astrophysical Observatory
BCE	Before Christian Era (aka BC)	DASCH	Digital Access to a Sky Century at Harvard
BCI	Biological Complexity Index	DBI	dual–beam imaging
BD	Bonner Durchmusterung	DCT	Discovery Channel Telescope (Lowell)
BDI	binary differential imaging	DE	Development Ephemeris (JPL)
BDKP	brown dwarf kinematics project	DEBRIS	Disk Emission via a Bias–free Reconnaissance in the IR/Sub–mm (Herschel–PACS survey)
BEER	BEaming, Ellipsoidal distortions, and Reflection	DEMONEX	DEdicated MONitor of EXotransits
BIPM	International Bureau of Weights and Measures (Bureau International des Poids et Mesures)	DENIS	Deep near–infrared Southern Sky Survey
BJD	Barycentric Julian Date	DES	Deep Ecliptic Survey
BKJD	Barycentric (Kepler) Julian Date	DFA	Detrended Fluctuation Analysis (transits)
BLG	bulge (in microlensing nomenclature)	DFDI	dispersed fixed–delay interferometer
BLS	Box–fitting Least Squares	DIAT	Dunlap Institute Arctic Telescope
BM2	Birch–Murnaghan second–order equation of state	DIMM	Differential Image Motion Monitor
BOAO	Bohyunsan Optical Astronomy Observatory	DIPOL	Double Image Polarimeter
BOES	Bohyunsan Optical Echelle Spectrograph	DIVA	Deutsches Interferometer für Vielkanalphotometrie und Astrometrie
BOKS	Burrell Optical Kepler Survey	DKIST	Daniel K. Inouye Solar Telescope
BOSS	Baryon Oscillation Spectroscopic Survey (SDSS)	DM	Durchmusterung (catalogue)
BP	Before Present (geohistorical dating)	DMS	Deep Multicolor Survey
BRITE	Bright Target Explorer	DODO	Degenerate Objects around Degenerate Objects (survey)
BSST	Bright Star Survey Telescope (Antarctica)	DSCOVER	Deep Space Climate Observatory (at L1)
BTA	Big Telescope Alt–azimuth (Russia)	DSLRL	Digital Single Lens Reflex (camera)
CAFE	Calar Alto Fiber–fed Echelle spectrograph (CAHA)	DST	Détection Spécialisée de Transits
CAHA	Centro Astronomico Hispano Alemán	DUNES	DUst around NEArby Stars (survey)
CAI	calcium–aluminium–rich inclusions (meteorite)	DUO	Disk Unseen Objects (microlensing)
CARMA	Combined Array for Research in mm–wave Astronomy	DXS/UDXS	Deep Extragalactic Survey (UKIDSS)



E-ELT	European Extremely Large Telescope	GPS/UGPS	Galactic Plane Survey (UKIDSS)
EBOP	Eclipsing Binary Orbit Program (code)	GPU	graphics processing unit
EDI	externally dispersed interferometer	GRAIL	Gravity Recovery and Interior Laboratory (satellite)
EEWS	Early Early Warning System (OGLE)	GRAVITY	adaptive optics assisted, near-infrared instrument (VLTI)
EIRP	equivalent isotropic radiated power	GREGOR	Gregorian solar telescope
ELC	light-curve synthesis code	GROND	Gamma-Ray Burst Optical/Near-IR Detector (ESO/MPG)
ELT	extremely large telescope	GROUSE	GROUnD-based Secondary Eclipse project
ENA	energetic neutral atoms	GRS	gamma ray spectrometer (Mars Odyssey)
EPD	External Parameter Decorrelation	GSFC	Goddard Space Flight Center
EPDS	Extreme Precision Doppler Spectrometer (WIYN)	GTC	Gran Telescopio Canarias
EPIC	Explicit Planetary Isentropic Coordinate model (GCM)	HARPS	High Accuracy Radial velocity Planet Searcher (ESO)
EPICA	European Project for Ice Coring in Antarctica (Dome C)	HAT	Hungarian Automated Telescope
EPICS	Exoplanet Imaging Camera and Spectrograph (E-ELT)	HATNet	Hungarian Automated Telescope Network
EPOCH	Exoplanet Observation and Characterisation (EPOXI)	HATPI	HAT upgrade
EPOXI	Exoplanet Observation and Deep Impact Extended Investigation	HATS	HAT-South
EPS	Ecliptic Plane Survey (Canada-France)	HD	Henry Draper (catalogue)
EROS	Expérience de Recherche d'Objets Sombres	HDA	high density amorphous (water phase)
ESA	European Space Agency	HDS	High Dispersion Spectrograph (Subaru)
ESI	Earth Similarity Index	HEC	Habitable Exoplanets Catalogue (University of Puerto Rico)
ESO	European Southern Observatory	HED	howardite-eucrite-diogenite (meteorite)
ESPRESSO	Echelle Spectrograph for PREcision Super Stable Observations (ESO)	HEK	Hunt for Exomoons with Kepler
EUV	extreme ultraviolet	HERMES	High-Efficiency and high-Resolution Mercator Echelle Spectrograph (Mercator telescope)
EVEREST	pixel level decorrelation of K2 light curves		High Efficiency and Resolution Multi-Element Spectrograph (AAT)
EVN	European VLBI Network	HESS	High Energy Stereoscopic System (gamma-ray)
EWS	Early Warning System (OGLE)	HESSI	High Energy Solar Spectroscopic Imager, now RHESSI
EXOFAST	IDL package for transit and radial velocity fitting	HET	Hobby-Eberly Telescope
EXOFIT	radial velocity fitting	HIDES	High Dispersion Echelle Spectrograph (OAO)
EXOSAT	European X-ray Observatory Satellite	HIP	Hipparcos (catalogue)
EXOTIME	EXOplanet search with the Timing MEthod	HIPPI	High Precision Polarimetric Instrument (AAT)
EXOTRANS	exoplanet transit simulator	HIRES	High Resolution Echelle Spectrometer (Keck)
EXPLORE	Extrasolar Planet Occultation Research	HIRES	High Resolution Spectrograph (E-ELT)
EXPOSE-E	ISS long-exposure experiment	HITEMP	opacity compilation
FAME	Full-sky Astrometric Mapping Explorer (USNO)	HITRAN	opacity compilation
FARGO	Fast Advection in Rotating Gaseous Objects (code)	HJD	heliocentric Julian Date
FAST	Five-hundred-meter Aperture Spherical radio Telescope	HJS	Harlan J. Smith Telescope (McDonald)
FD	Finite Difference (hydrodynamic code)	HMI	Helioseismic and Magnetic Imager (SDO)
FEROS	Fiber-fed Extended Range Optical Spectrograph (ESO)	HOSTS	Hunt for Observable Signatures of Terrestrial Systems
FGS	Fine Guidance Sensor (HST)	HPF	Habitable zone Planet Finder (HET)
FIES	Fibre-fed Echelle Spectrograph (NOT)	HR	Hertzprung-Russell (diagram)
FIRST	Far Infrared and Submillimetre Space Telescope (ESA)	HRS	High-Resolution Spectrograph (HET)
FK	Fundamental Catalogue (FK1-FK6)	HST	Hubble Space Telescope
FLAMES	Fibre Large Array Multi Element Spectrograph (ESO)	HZ	habitable zone
FLI	fast Lyapunov indicator (chaos measure)	IAU	International Astronomical Union
FMS	Flexible Modelling System (GCM)	IBEX	Interstellar Boundary Explorer (NASA)
FOAM	Fast Ocean Atmosphere Model (GCM)	ICE-T	International Concordia Explorer Telescope (Dome C)
FOCAL	Fast Outgoing Cyclopean Astronomical Lens (lensing)	ICRF	International Celestial Reference Frame
FRB	fast radio burst	ICRS	International Celestial Reference System
FRESIP	FRequency of Earth-Size Inner Planets (pre-Kepler study)	IDL	Interactive Data Language
FTS	Fourier transform spectrometer	IDPS	International Deep Planet Survey
G-CLEF	GMT-CfA Large Earth Finder (GMT)	IERS	International Earth Rotation and Reference Systems Service (formerly, International Earth Rotation Service)
GALEX	Galaxy Evolution Explorer	IFS	Integral Field Spectroscopy
GAME	Gravitation Astrometric Measurement Experiment	IGR	INTEGRAL Gamma-Ray (source)
GAPS	Global Architecture of Planetary Systems (HARPS)	IGRINS	Immersion Grating Infrared Spectrometer (McDonald)
GASPS	Gas and Dust in Protoplanetary Disks (Herschel)	IMCCE	Inst. Celestial Mechanics and Computation of Ephemerides
GBNCC	Green Bank North Celestial Cap (pulsar survey)	INPOP	Intégration Numérique Planétaire de l'Observatoire de Paris
GCM	General Circulation Model (atmospheres)	INT	Isaac Newton Telescope (La Palma)
GCS/UGCS	Galactic Clusters Survey (UKIDSS)	IPCC	Intergovernmental Panel on Climate Change
GEMS	glass with embedded metal and sulphides	IRAC	Infrared Array Camera (Spitzer)
GENGA	gravitational encounters in N-body simulations	IRAM	Institut de Radioastronomie Millimétrique de Grenoble
GENIE	Ground based European Nulling Interferometer Experiment	IRAS	Infrared Astronomical Satellite
GEST	Galactic Exoplanet Survey Telescope	IRD	Infrared Doppler Instrument (Subaru)
GFDL	Geophysical Fluid Dynamics Laboratory (GCM)	IRDIS	infrared dual-band imager and spectrograph (SPHERE)
GIANO	Near infrared high resolution échelle spectrograph (TNG)	IRFM	infrared flux method
GJ	Gliese Jahreiß (catalogue)	IRIS	Infrared Interferometer Spectrometer and Radiometer (Voyager)
GLAO	ground layer adaptive optics	IRS	Infrared Spectrograph (Spitzer)
GMAN	Global Microlensing Alert Network	IRSF	InfraRed Survey Facility (S. Africa)
GMRT	Giant Metrewave Radio Telescope	IRTF	Infrared Telescope Facility
GMT	Giant Magellan Telescope	ISM	interstellar medium
GOBE	Great Ordovician Biodiversification Event	ISO	Infrared Space Observatory (ESA)
GOME	Global Ozone Monitoring Experiment (ERS-2)	ISS	International Space Station
GP-EBOP	Gaussian Process EBOP	IUPAC	International Union of Pure and Applied Chemistry
GPI	Gemini Planet Imager	IWA	inner working angle (coronagraphy)

J-MAPS	Joint Milliarcsecond Pathfinder Survey	MIPS	Multi-Band Imaging Photometer (Spitzer)
JANAF	Joint Army-Navy-NASA-Air Force thermochemical tables	MIRC	Michigan Infra-Red Combiner (CHARA)
JASMINE	Japan Astrometry Satellite Mission for INfrared Exploration	MIRI	Mid-Infrared Instrument (JWST)
JCMT	James Clerk Maxwell Telescope	MIT	Massachusetts Institute of Technology
JD	Julian Date	MJD	Modified Julian Date
JKTEBOP	John Kevin Taylor's EBOP code	MK	Morgan-Keenan (spectral classification)
JPL	Jet Propulsion Laboratory	MMEN	minimum-mass extrasolar nebula
JWST	James Webb Space Telescope	MMR	mean motion resonance
		MMSN	minimum-mass solar nebula
KASC	Kepler Asteroseismic Science Consortium	MMT	Multi-Mirror Telescope
KBO	Kuiper Belt object	MOA	Microlensing Observations in Astrophysics
KCTF	Kozai cycles with tidal friction	MOND	Modified Newtonian Dynamics
KELT	Kilodegree Extremely Little Telescope	MORIS	MIT Optical Rapid Imaging System
KEOPS	Kiloparsec Explorer for Optical Planet Search (Dome C)	MOST	Microvariability and Oscillations of Stars (satellite)
KIC	Kepler Input Catalogue	MPC	Minor Planet Center
KIN	Keck Interferometric Nuller	MPF	Microlensing Planet Finder
KIS	Kepler-INT Survey	MPG	Max-Planck-Gesellschaft (Max-Planck Society)
KLIP	Karhunen-Loève Image Processing	MPIA	Max-Planck-Institute for Astronomy (Heidelberg)
KLIP-FM	KLIP forward modeling	MPS	Microlensing Planet Search
KOI	Kepler Object of Interest	MRI	magneto-rotational instability
KPNO	Kitt Peak National Observatory	MRS	medium-resolution spectroscopy (SPHERE)
KVA	Swedish telescope (La Palma)	MSC	Multiple Star Catalogue
		MUSCLES	Measurements of the Ultraviolet Spectral Characteristics of Low-mass Exoplanetary Systems
LABOCA	Large APEX BOlometer Camera (APEX)	MWA	Murchison Widefield Array (radio)
LAMOST	Large Sky Area Multi-Object Fibre Spectroscopic Telescope		
LAS/ULAS	Large Area Survey (UKIDSS)	NACO	NAOS-CONICA (ESO)
LBT	Large Binocular Telescope	NACRE	Nuclear Astrophysics Compilation of Reaction Rates
LBTI	Large Binocular Telescope Interferometer	NAOC	National Astronomical Observatories of China
LCO	Las Campanas Observatory	NAOJ	National Astronomical Observatory of Japan
LCO-GT	LCO Gemini Telescope	NAOS	Nasmyth Adaptive Optics System (ESO)
LCOGT	Las Cumbres Observatory Global Network	NASA	National Aeronautics and Space Administration
LCPB	L-chondrite parent body breakup	NCAR	National Center for Atmospheric Research (USA)
LCROSS	Lunar CRater Observation and Sensing Satellite	NEA	nearth-Earth asteroid
LDA	low density amorphous (water phase)	NEAT	Nearby Earth Astrometric Telescope
LDEF	Long Duration Exposure Facility (Space Shuttle)	NED	NASA/IPAC Extragalactic Database
LDTK	Limb Darkening Toolkit	NEMESIS	radiative transfer and retrieval code
LEECH	LBTI Exozodi Exoplanet Common Hunt (LBT)	NEO	near-Earth object
LHS	Luyten Half Second (catalogue)	NGC	New General Catalogue (of Nebulae and Clusters of Stars)
LINEAR	Lincoln Near-Earth Asteroid Research	NGTS	Next Generation Transit Survey
LIP	Large Igneous Provinces	NIAC	NASA Institute for Advanced Concepts
LIPAD	Lagrangian Integrator for Planetary Accretion and Dynamics	NICI	Near-Infrared Coronagraphic Imager (Gemini)
LISA	Laser Interferometer Space Antenna (gravitational waves)	NICMOS	Near Infrared Camera and Multi-Object Spectrometer (HST)
LMC	Large Magellanic Cloud	NIISS	Near Infrared Imager and Slitless Spectrograph
LMD	Laboratoire de Météorologie Dynamique, Paris	NIRC	Near Infrared Camera (Keck)
LMDZ	LMD GCM	NIR-OSETI	Near-Infrared Optical SETI
LMIRCAM	Large Binocular Telescope mid-infrared camera (LBT)	NISP-H	Near Infrared Spectrometer and Photometer (Euclid)
LMXB	low-mass X-ray binary	NIST	National Institute of Standards and Technology
LOCI	Locally Optimised Combination of Images	NITES	Near-Infrared Transiting ExoplanetS telescope
LOFAR	Low-Frequency Array (radio)	NLTT	New Luyten Two-Tenths (catalogue)
LOLA	Lunar Orbiter Laser Altimeter	NOEMA	Northern Extended Millimeter Array
LOUPE	Lunar Observatory for Unresolved Polarimetry of Earth	NOT	Nordic Optical Telescope
LRs	low-resolution spectroscopy (SPHERE)	NPARSEC	NTT PARallaxes of Southern Extremely Cool objects (ESO)
LSST	Large Synoptic Survey Telescope	NPOI	Navy Prototype Optical Interferometer (USNO)
LTE	local thermodynamic equilibrium	NRAO	National Radio Astronomy Observatory
LUNA	transit algorithm for exomoons	NRES	Network of Robotic Echelle Spectrographs (LCOGT)
LUVUIR	Large UV/Optical/IR Surveyor	NSF	National Science Foundation (USA)
		NTT	New Technology Telescope
MACHO	Massive Astrophysical Compact Halo Object	OAo	Okayama Astrophysical Observatory
MAORY	Multi-conjugate Adaptive Optics RelaY (E-ELT)	OBSS	One Billion Star Satellite
MARCS	Model Atmospheres in Radiative and Convective Scheme	ODC	Optical Differentiation Coronagraph
MARVELS	Multi-object APO Radial Velocity Exoplanet Large-area Survey (SDSS)	OFXB	Observatoire François-Xavier Bagnoud
MASTER	Mobile Astronomical System of Telescope Robots	OGCM	ocean GCM
MCAO	Multi-Conjugate Adaptive Optics	OGLE	Optical Gravitational Lens Experiment
MCMC	Monte Carlo Markov Chain	OHP	Observatoire de Haute Provence
MDI	Michelson Doppler Imager (SOHO)	OP	Oceanic Provinces
MDM	Michigan-Dartmouth-MIT observatory (Kitt Peak)	OPAL	opacity code
MEGNO	Mean Exponential Growth factor of Nearby Orbits	ORM	Observatorio del Roque de los Muchachos, La Palma
MEMS	Micro-Electro-Mechanical System technology	OSETI	Optical SETI
MESS	Multi-purpose Exoplanet Simulation System	OSIRIS	Optical System for Imaging and low Resolution Integrated Spectroscopy (GTC)
METI	Messaging to Extraterrestrial Intelligence		
METIS	Mid-Infrared ELT Imager and Spectrograph (E-ELT)	OSSOS	Outer Solar System Origins Survey (Canada-France)
MEarth	M dwarf search for Earth-like planets	OWL	Overwhelmingly Large Telescope
MHD	magnetohydrodynamics		
MIDEX	Medium-Class Explorers (NASA)	PACS	Photoconductor Array Camera and Spectrometer (Herschel)
MIKE	Magellan Inamori Kyocera Echelle spectrograph	PAH	polycyclic aromatic hydrocarbons

PALMS	Planets Around Low-Mass Stars	RVS	Radial Velocity Spectrometer (Gaia)
PANOPTES	Panoptic Astronomical Networked Observatories for a Public Transiting Exoplanets Survey	RXTE	Rossi X-Ray Timing Explorer (satellite)
PARAS	PRL Advanced Radial-velocity All-sky Search (India)	SAAO	South African Astronomical Observatory
PARASOL	Polarisation and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (satellite)	SAINT-EX	Search and Characterisation of Transiting Exoplanets
PARSEC	Parallaxes of southern extremely cool objects	SALT	Southern African Large Telescope (SAAO)
PASTIS	Planet Analysis and Small Transit Investigation Software	SAO	Smithsonian Astrophysical Observatory
PCA	principle component analysis	SARG	Spettrografo ad Alta Risoluzione per Galileo (TNG)
PCEB	post-common-envelope binary	SARS	Simultaneous Additive and Relative SysRem Algorithm
PCXP	Project 1640 Data Cube Extraction Pipeline	SBM	Sky Brightness Monitor (Dome C)
PDI	Polarised Differential Imaging	SCAM	STJ camera
PEARL	Polar Environment Atmospheric Research Laboratory	SCIAMACHY	SCanning Imaging Absorption Spectrometer for Atmospheric CHartography (ENVISAT)
PEPSI	Potsdam Echelle Polarimetric and Spectroscopic Instrument (LBT)	SDI	simultaneous differential imaging
PEST	Perth Exoplanet Survey Telescope	SDO	Solar Dynamics Observatory
PETIT	Pressure-Temperature Iterator and Spectral Emission Calculator for Planetary Atmospheres	SDSS	Sloan Digital Sky Survey
PETM	Paleocene-Eocene Thermal Maximum	SEEDS	Strategic Exploration of Exoplanets and Disks with Subaru
PFI	Planet Formation Imager (TMT)	SEGUE	Sloan Extension for Galactic Understanding and Exploration
PFS	Planet Finder Spectrograph (Magellan)	SEICA	Second-generation Exoplanet Imager with Coronagraphic Adaptive optics
PHA	Potentially Hazardous Asteroid	SEIT	Second Earth Imager for TMT
PHASES	Palomar High-precision Astrometric Search for Exoplanet Systems	SEM	scanning electron microscope
PHI	Planet Habitability Index	SETI	Search for Extraterrestrial Intelligence
PHL	Planet Habitability Laboratory (University of Puerto Rico)	SGP	south Galactic pole
PHOENIX	stellar atmosphere modeling code	SI	International System of Units (Système International d'Unités)
PIAA	Phase-Induced Amplitude Apodisation coronagraph	SIDRA	Signal Detection using Random-Forest Algorithm
PICTURE	Planetary Imaging Concept Testbed Using a Recoverable Experiment (satellite series)	SIM	Space Interferometry Mission
PIKAIA	genetic search algorithm	SIMBAD	Set of Identifications, Measurements, and Bibliography for Astronomical Data
PIONIER	Precision Integrated-Optics Near-infrared Imaging Experiment (VLTI)	SIMP	Sondage Infrarouge de Mouvement Propre (CTIO)
PISCES	Planets in Stellar Clusters Extensive Search	SINFONI	Spectrograph for INtegral Field Observations in the Near-IR
PIZZA	Phase-induced zonal Zernike apodisation	SKA	Square Kilometre Array
PLANET	Probing Lensing Anomalies NETWORK (microlensing)	SMA	Submillimeter Array (Hawaii)
PLATO	PLAnetary Transits and Oscillations of stars (satellite)	SMARTS	Small and Moderate Aperture Research Telescope System
PLT	Polar Large Telescope	SMO	Submillimeter Observatory (Caltech)
PMS	pre-main sequence stars	SMOW	Standard Mean Ocean Water (standard isotopic ratios)
POTS	Pre-OmegaTranS survey	SNC	shergottites, nakhlites, and chassignites (meteorites)
PPA	pupil phase apodisation (coronagraph)	SNREI	Spherical, NonRotating, Elastic, and Isotropic (Earth model)
PPMXL	Positions, proper motions, 2MASS- and optical photometry (catalogue)	SOAP(-T)	Spot Oscillation And Planet (software)
PREM	Preliminary Reference Earth Model	SOAR	Southern Astrophysical Research telescope (Cerro Pachón)
PRF	pixel response function (Kepler)	SOFIA	Stratospheric Observatory for Infrared Astronomy
PRIMA	Phase-Referenced Imaging and Microarcsecond Astrometry (ESO)	SOHO	Solar and Heliospheric Observatory
PRISM	Planetary Retrospective Integrated Star-spot Model	SOI	SOAR Optical Imager
PRVS	Precision Radial Velocity Spectrometer (Gemini)	SONG	Stellar Observations Network Group
PSC	Point Source Catalogue (2MASS)	SONS	SCUBA-2 Observations of Nearby Stars (JCMT)
PSO	Pan-STARRS Object	SONYC	Substellar Objects in Nearby Young Clusters (collaboration)
PSR	pulsar	SOPHIE	Spectrographe pour l'Observation des Phénomènes des Intérieurs stellaires et des Exoplanètes
PSST	Planet Search Survey Telescope	SORCE	Solar Radiation and Climate Experiment (satellite)
PTF	Palomar Transient Factory	SPE	Solar/Stellar Proton Event
PTFM	PTF M dwarf survey	SPECULOOS	Search for habitable Planets Eclipsing ULtra-coOL Stars
PTFO	PTF Orion survey	SPH	Smoothed-Particle Hydrodynamics (hydrodynamic code)
PTI	Palomar Testbed Interferometer	SPHERE	Spectro-Polarimetric High-contrast Exoplanet Research (VLT) star-planet interactions
PUMA	Portable University Model of the Atmosphere (GCM)	SPI	Space Infra-Red Telescope for Cosmology and Astrophysics
PYRATBAY	Python Radiative Transfer in Bayesian Framework	SPICES	Spectro-Polarimetric Imaging and Characterisation of Exoplanet Systems (satellite)
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System	SPIRE	Spectral and Photometric Imaging Receiver (Herschel)
QATS	Quasi-periodic Automated Transit Search	SPOCS	Spectroscopic Properties of Cool Stars
QBO	quasi-biennial oscillation (Earth GCM)	SPOTROD	semi-analytical model for spotted star transits
QES	Qatar Exoplanet Survey	STACEE	Solar Tower Atmospheric Cherenkov Effect Experiment
RA	right ascension	STARE	STellar Astrophysics and Research on Exoplanets
RADEN	diatomic opacities (Moscow State University)	STEPS	STellar Planet Survey (astrometry)
RATS	Rapid Temporal Survey (Kepler)	STEPSS	Survey for Transiting Extrasolar Planets in Stellar Systems
RDI	reference star differential imaging	STEREO	Solar TERrestrial RELations Observatory
RECONS	Research Consortium on Nearby Stars	STIP(S)	systems with tightly packed inner planets
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager	STIS	Space Telescope Imaging Spectrograph (HST)
RISE	Rapid Imaging Search for Exoplanets (Liverpool Telescope)	STJ	superconducting tunneling junction
RM	Rossiter-McLaughlin effect	STP	standard temperature and pressure
ROSAT	ROentgen SATellite	STRESS	STEREO TRansiting Exoplanet and Stellar Survey
ROXS	$\rho$ Oph X-ray source	SWEEPS	Sagittarius Window Eclipsing Extrasolar Planet Search
RVLIN	fitting routine for Keplerian curves	TAI	International Atomic Time (Temps Atomique International)
		TAP	Transit Analysis Package
		TAPIR	TrAnsit PlannIng and Reconnaissance (KELT)
		TASTE	The Asiago Survey for Timing transit variations of Exoplanets

TAU	Thousand Astronomical Unit (satellite concept)	UV	ultraviolet
TCB	Barycentric Coordinate Time (Temps Coordonnée Barycentrique)	UVES	Ultraviolet and Visual Echelle Spectrograph (ESO)
TCE	threshold crossing event (Kepler)	VCSELS	Vertical-cavity surface-emitting laser systems
TDB	Barycentric Dynamical Time (Temps Dynamique Barycentrique)	VERITAS	Very Energetic Radiation Imaging Telescope Array System
TDT	Terrestrial Dynamical Time (Temps Dynamique Terrestre)	VHDA	very high density amorphous (water phase)
TDV	transit duration variations	VHS	VISTA Hemisphere Survey
TEA	Thermochemical Equilibrium Abundances	VIKING	VISTA Kilo Degree Infrared Galaxy Survey
TEDI	TripleSpec Exoplanet Discovery Instrument	VIM	variability-induced mover/motion
TEP	Transits of Extrasolar Planets network	VIRCAM	VISTA infrared camera
TERMS	Transit Ephemeris Refinement and Monitoring Survey	VIRGO	Variability of solar Irradiance and Gravity Oscillations (SOHO)
TERRA	Template-Enhanced Radial velocity Re-analysis Application	VIS	Visible Instrument (Euclid)
TESS	Transiting Exoplanet Survey Satellite	VISTA	Visible and Infrared Survey Telescope for Astronomy (ESO)
TFA	trend-fitting algorithm (transits)	VLA	Karl G. Jansky Very Large Array (radio)
TGAS	Tycho–Gaia Astrometric Solution	VLBA	Very Long Baseline Array
THESIS	Transiting Habitable-zone Exoplanet Spectroscopy Infrared Spacecraft (NASA MIDEX proposal)	VLBI	Very Long Baseline Interferometer
THOR	GPU-based GCM	VLSS	VLA Low-Frequency Sky Survey
TIFR	Tata Institute of Fundamental Research	VLT	Very Large Telescope (ESO)
TMA	three-mirror anastigmatic (telescope)	VLTi	Very Large Telescope Interferometer (ESO)
TMT	Thirty Metre Telescope	VNC	visible nulling coronagraph
TNG	Telescopio Nazionale Galileo (La Palma)	VSI	VLTi Spectro-Imager (ESO)
TNO	trans-Neptunian objects	VSMOW	Vienna Standard Mean Ocean Water (standard isotopic ratios)
TNT	Thai National Telescope	VST	VLT Survey Telescope (ESO)
TODCOR	cross-correlation algorithm for spectroscopic binary	VSTAR	Versatile Software for Transfer of Atmospheric Radiation
TPF	Terrestrial Planet Finder	VTT	Vacuum Tower Telescope (solar)
TPF-C/I/O	TPF coronagraph/interferometer/(external) occulter	VVV	VISTA Variables in the Via Láctea
TPS	Transit Planet Search	WASP	Wide Angle Search for Planets
TRACE	Transition Region and Coronal Explorer	WATTS	Wide Angle Transit Telescope Search
TRACER	Transit Characterisation Explorer	WD	white dwarf
TRADES	TRAnsits and Dynamics of Exoplanetary Systems	WDS	Washington Double Star (catalogue)
TRANSIT	radiative-transfer code for planetary atmospheres	WFC	Wide Field Camera (HST)
TRAPPIST	Transiting Planets and Planetesimals Small Telescope	WFCAM	Wide Field Camera (UKIRT)
TRES	Tillinghast Reflector Echelle Spectrograph	WFI	Wide Field Imager (Siding Spring)
TrES	Trans-Atlantic Exoplanet Survey network	WFIRST	Wide Field Infrared Survey Telescope
TRILEGAL	TRIdimensional modeL of the GALaxy	WGPSN	Working Group for Planetary System Nomenclature (IAU)
TT	Terrestrial Time (Temps Terrestre)	WHT	William Herschel Telescope
TTV	transit timing variations	WIRED	WISE InfraRed Excesses around Degenerates survey
TWINS	Two Wide-angle Imaging Neutral-atom Spectrometers	WISE	Wide-field Infrared Survey Explorer
UCDTS	Ultra-Cool Dwarfs Transit Survey (TRAPPIST)	WIYN	Wisconsin Indiana Yale and National Optical Astronomy Observatories (telescope)
UCLES	University College London Echelle Spectrograph (AAT)	WMAP	Wilkinson Microwave Anisotropy Probe
UDS/UUDS	Ultra Deep Survey (UKIDSS)	WSRT	Westerbork Synthesis Radio Telescope
UFO	unidentified flying object	WTS	WFCAM Transit Survey
UGAMOP	diatomic opacities (University of Georgia)	XAO	extreme adaptive optics
UKIDSS	UK Infrared Digital Sky Survey	XMM	X-ray Multi-Mirror Mission (XMM–Newton)
UKIRT	UK Infrared Telescope	XO	XO telescope (Hawaii)
URL	Uniform Resource Locator (www)	XUV	extreme ultraviolet
USNO	US Naval Observatory	ZIMPOL	Zurich imaging polarimeter
USP	ultra-short-period (planets), $P < 1$ d		
UT	Universal Time		
UTC	Coordinated Universal Time		

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# Appendix C. Radial velocity exoplanets

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This appendix includes objects appearing in the online NASA Exoplanet Archive as of 31 December 2017, along with a small number of other candidates or retracted systems.

These notes list some key attributes of the system to underline its particular interest, give some indication of the attention the object has received (through the length of the bibliography), and provide a concise note on each paper to serve as a guide to the literature and a narrative of the progress in understanding the system. It makes no claim for completeness, and CDS–SIMBAD should be consulted for more details.

It includes only cross-identifications which are relevant in context, e.g., as used in the early discovery literature. CDS–SIMBAD or the NASA Exoplanet Archive should be consulted for other aliases. If a different alias was used in the NASA archive, this is explicitly noted.

The electronic version includes three classes of hyperlink: the object identifier (in bold) is linked to the host star page of the NASA Exoplanet Archive (it will be invalid if their syntax changes); each citation is linked to the bibliography; and the > icon following the citation links to the relevant ADS page.

**Radial velocity planets which transit:** A small number of planets discovered through radial velocity measurements have been subsequently found to transit (such as HD 189733 and HD 209458). Since the majority of the corresponding literature relates to the transits, a cross-reference is made to the appendix on transiting planets, where the full bibliography is listed.

**Transiting systems with radial velocity discoveries:** Similarly, for systems discovered through transit photometry, where other planets were subsequently discovered by radial velocity measurements, the radial velocity discoveries are noted explicitly here, but also cross-referenced to the more complete bibliography in the appendix on transiting planets.

## Notes on individual systems

### Constellation identifiers

***v*And** ≡ HR 458; 3-planet system with planets c and d in eccentric orbits; planet e unconfirmed; discovery of planet b, and evidence for planet c (Butler et al., 1997)> stellar properties (Baliunas et al., 1997)> stellar properties (Fuhrmann et al., 1998)> discovery of planets c and d (Butler et al., 1999)> line profile variations (François et al., 1999)> orbit stability in the 3-planet system (Laughlin & Adams, 1999)> mass limits from Hipparcos astrometry (Mazeh et al., 1999)> search for radio emission (Bastian et al., 2000)> models of the spacing of planetary systems (Laskar, 2000)> orbit stability (Rivera & Lissauer, 2000)> orbit stability (Stepinski et al., 2000)> tidal constraints on mass (Trilling, 2000)> orbit stability and planet eccentricities (Barnes & Quinn, 2001)> apsidal alignment in planets c and d (Chiang et al., 2001)> orbit stability (Ito & Miyama, 2001)>

orbit stability (Jiang & Ip, 2001)> orbit stability and planet inclinations (Lissauer & Rivera, 2001)> eccentricity excitation and apsidal resonance capture (Chiang & Murray, 2002)> limits on reflected light from planet b (Collier Cameron et al., 2002)> imaging of co-moving stellar companion (Lowrance et al., 2002)> tidal, spin, and dynamical evolution (Mardling & Lin, 2002)> expectation of apsidal oscillation (Michtchenko & Malhotra, 2004)> ELODIE observations (Naef et al., 2004)> planet–planet scattering and coupled orbit evolution (Ford et al., 2005)> dynamical survival of planet b (Nagasawa & Lin, 2005)> orbit dependence of chromospheric activity and magnetic interaction (Shkolnik et al., 2005)> phase-dependent infrared brightness variations from Spitzer (Harrington et al., 2006)> orbit stability (Michtchenko et al., 2006)> magnetic communication in hot Jupiters (Preusse et al., 2006)> proximity to 5:1 resonance (Libert & Henrard, 2007)> orbit stability (Rivera & Haghighipour, 2007)> enhanced stellar magnetic activity due to close-in planet (Lanza, 2008)> consistency with a stable Kozai-resonant state (Libert & Tsiganis, 2009a)> phase-dependent infrared brightness variations from Spitzer, and atmospheric circulation (Crossfield et al., 2010)> 30° relative inclination of planets c and d from HST-FGS (McArthur et al., 2010)> origin of the mutually inclined orbits of planets c and d (Barnes et al., 2011c)> planet e inferred from Keplerian fit (Curiel et al., 2011)> magnetic interaction with host star (Kopp et al., 2011)> limits on X-ray variability due to star–planet interaction (Poppenhaeger et al., 2011)> improved mass limits from Hipparcos astrometry (Reffert & Quirrenbach, 2011)> Bayesian modeling (Tuomi et al., 2011)> stellar parameters from interferometry with CHARA–VEGA (Ligi et al., 2012)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)> 3d dynamical stability analysis (Deitrick et al., 2015)> detection of H<sub>2</sub>O-vapour from planet radial velocity from Keck–NIRSPEC (Piskorz et al., 2017)> hot Jupiter migration attributed to disk interactions (Wang et al., 2017d)>

**14 And** discovery (Sato et al., 2008b)> interferometry (Ligi et al., 2012)>

**ξ Aql** discovery (Sato et al., 2008a)>

**91 Aqr** ≡ HD 219449; discovery (Mitchell et al., 2013)>

**μ Ara** ≡ HD 160691 (as listed in NASA); 4-planet system; discovery of planet b (Butler et al., 2001)> evidence for planet c (Jones et al., 2002a)> dynamical constraints on planet c (Kiseleva-Eggleton et al., 2002)> dynamical stability (Bois et al., 2003)> dynamical stability (Goździewski et al., 2003)> discovery/confirmation of planet c (McCarthy et al., 2004)> discovery/confirmation of planet c (Santos et al., 2004a)> asteroseismology (Bouchy et al., 2005a)> asteroseismology (Bazot et al., 2005)> dynamical constraints on the 2-planet system (Goździewski et al., 2005a)> orbital stability (Goździewski et al., 2007)> discovery of planets d and e (Pepe et al., 2007)> dynamical constraints on the 4-planet system (Short et al., 2008)> asteroseismology (Soriano & Vauclair, 2008)> asteroseismology (Soriano & Vauclair, 2010)> effects of oscillation and stellar granulation (Dumusque et al., 2011c)> mass constraints from Hipparcos astrometry (Reffert & Quirrenbach, 2011)> habitability of hypothetical exomoon (Hinkel & Kane, 2013a)> gravitational quantisation of orbits (Geroyannis, 2015)>

**α Ari** discovery and unstable acoustic pulsations (Lee et al., 2011a)> see also earlier observations (Kim et al., 2006)>

**30 Ari B** see transiting systems

**τ Boo** ≡ HR 5185 ≡ HD 120136; discovery (Butler et al., 1997)> stellar properties (Baliunas et al., 1997)> line profiles (Brown et al., 1998b)> line profiles (Brown et al., 1998a)> stellar properties (Fuhrmann et al., 1998)> limits on reflected light (Charbonneau et al., 1999)> claimed

- detection of reflected light (Collier Cameron et al., 1999)> search for radio emission (Bastian et al., 2000)> limits on CH<sub>4</sub> (Wiedemann et al., 2001)> search for stellar companions (Patience et al., 2002)> limits on reflected light (Leigh et al., 2003b)> dynamical stability (Musielak et al., 2005)> stellar magnetic field and spin-orbit synchronisation (Catala et al., 2007)> search for radio emission (Lazio & Farrell, 2007)> stellar magnetic field and differential rotation (Donati et al., 2008)> enhanced stellar magnetic activity due to close-in planet (Lanza, 2008)> stellar variability induced by planet orbit (Walker et al., 2008)> limits on polarisation variability (Fares et al., 2009)> polarisation (Lucas et al., 2009)> magnetic field and radio emission (Reiners & Christensen, 2010)> CO absorption and orbit inclination (Brogi et al., 2012b)> X-ray studies (Poppenhaeger et al., 2012b)> stellar variability induced by planet orbit (Ruban & Arkharov, 2012)> CO absorption and orbit inclination (Rodler et al., 2012)> search for radio emission (Stroe et al., 2012)> models of stellar wind and planetary radio emission (Vidotto et al., 2012)> stellar magnetic field topology (Fares et al., 2013)> search for radio emission (Hallinan et al., 2013)> CO absorption and orbit inclination (Rodler et al., 2013b)> detection of H<sub>2</sub>O from high-resolution L-band spectroscopy (Lockwood et al., 2014)> magnetic activity and asteroseismology from HARPS-N (Borsa et al., 2015)> time scales of radio emission variability (See et al., 2015)> evolving magnetic topology (Mengel et al., 2016)> temporal variability of the stellar wind (Nicholson et al., 2016)> four-month stellar chromospheric and coronal activity cycle (Mittag et al., 2017)> sub-year magnetic chromospheric activity cycle and activity phase jumps (Schmitt & Mittag, 2017)>
- $\alpha$  Cen A/B** unconfirmed (not listed in NASA archive); claimed Earth-mass planet in 3-d orbit around component B of a close stellar binary (Dumusque et al., 2012)> feasibility of probing by radar (Rzhiga, 1985)> as an example of the elliptic restricted problem (Benet, 1988)> Li abundance (King et al., 1997b)> <sup>9</sup>Be abundance of stellar components (King et al., 1997a)> analysis of planetary stability (Wiegert & Holman, 1997)> theoretical stellar models (Guenther & Demarque, 2000)> gravitational lenses (Maccone, 2000)> planetary limits from ESO Coude search (Endl et al., 2001)> as an example of formation of terrestrial planets in close binary systems (Barbieri et al., 2002)> terrestrial planet formation (Quintana et al., 2002)> asteroseismology (Thévenin et al., 2002)> asteroseismology (Thoul et al., 2003)> oscillation frequencies and mode lifetimes (Bedding et al., 2004)> theoretical stellar models including seismology (Eggenberger et al., 2004c)> solar-like oscillations of host star (Kjeldsen et al., 2005)> seismology (Miglio & Montalbán, 2005)> formation and detectability of terrestrial planets (Guedes et al., 2008)> difficulties of accretion (Thébaud et al., 2008)> planet formation in habitable zone (Thébaud et al., 2009)> planetesimal accretion in binaries (Xie et al., 2010b)> role of snowball growth (Xie et al., 2010a)> planetary detection limits with stellar noise (Dumusque et al., 2011c)> Bayesian analysis of stellar parameters (Bazot et al., 2012)> discovery of planet b (Dumusque et al., 2012)> oscillation in the habitable zone (Forgan, 2012)> models of circumstellar disk (Müller & Kley, 2012)> dynamical stability of planets (Popova & Shevchenko, 2012)> detectability with ELTs (Crossfield, 2013)> habitable zone (Eggl et al., 2013a)> effects of noise in the radial velocity signal (Hatzes, 2013b)> suggestion of planet around  $\alpha$  Cen A from abundance analysis (Hinkel & Kane, 2013b)> habitable zone (Kaltenegger & Haghighipour, 2013)> detectability of polarisation with SPHERE-ZIMPOL (Milli et al., 2013)> planet formation in small separation binaries (Rafikov, 2013b)> dynamical stability of terrestrial planets (Andrade-Ines & Michtchenko, 2014)> probing by interstellar radar (Scheffer, 2014)> improved accuracy from scattered light analysis (Bergmann et al., 2015)> HST transit search (Demory et al., 2015)> radial velocities from Mt John-HERCULES (Endl et al., 2015)> planet mass from dynamical stability (Plavchan et al., 2015)> planet formation in stellar binaries (Rafikov & Silsbee, 2015b)> Milankovitch cycles in eccentricity, obliquity, and precession (Forgan, 2016)> simulation of Gaia astrometric data for  $\alpha$  Cen A (Huang & Ji, 2016)> possible circumbinary configurations (Popova & Shevchenko, 2016a)> long-term stability (Quarles & Lissauer, 2016)> planetary signal attributed to window function (Rajpaul et al., 2016)> effects of Proxima Cen on planet formation (Worth & Sigurdsson, 2016)> imaging search from the VISTA-VVV near-infrared survey (Beamin et al., 2017)> stability regions for S-type planets in Lidov-Kozai resonance (Giuppone & Correia, 2017)> deceleration of interstellar photon sails into bound orbits (Heller & Hippke, 2017)> astrometric planet detection with Gaia around  $\alpha$  Cen A (Huang & Ji, 2017)> orbit of Proxima Cen (Kervella et al., 2017)> long-term stability of circumstellar and circumbinary orbits (Quarles et al., 2018)> planet constraints from HARPS radial velocity measurements over 10 years (Zhao et al., 2018a)>
- Proxima Cen** discovery (Anglada-Escudé et al., 2016a)> earlier considerations of habitable zone (Endl & Kürster, 2008)> possible structure and composition (Brugger et al., 2016)> space weather (Garraffo et al., 2016)> prospects for characterising atmosphere (Kreidberg & Loeb, 2016)> habitability: irradiation, rotation and volatile inventory (Ribas et al., 2016)> habitability: climates and observability (Turbet et al., 2016)> effects on planet formation in  $\alpha$  Cen (Worth & Sigurdsson, 2016)> ALMA discovery of dust belts at 1–4 au, with a compact emission source (Anglada et al., 2017)> simulations of resolved surface imaging from reflected light (Berdyugina & Kuhn, 2017)> probabilistic constraints on mass, radius and composition (Bixel & Apai, 2017)> climate simulations using the UK Meteorological Office Unified Model (Boutle et al., 2017)> orbit eccentricity from radial velocity data of  $e = 0.25$  (Brown, 2017)> constraint on super-Earth interiors from stellar abundances (Brugger et al., 2017)> predicted radio detectability of 100 mJy at 0.02–3 MHz (Burkhart & Loeb, 2017)> predicted system multiplicity as a function of formation scenario (Coleman et al., 2017)> stellar noise in the radial velocity data (Damasso & Del Sordo, 2017)> habitability dependence on ion escape rates and intrinsic magnetic dipole field (Dong et al., 2017b)> atmospheric escape time scale due to high stellar extreme ultraviolet flux (García-Sage et al., 2017)> variable incident flux due to obliquity and eccentricity (Kane & Torres, 2017)> orbit and habitability as a function of orbit inclination (Kane et al., 2017a)> orbital motion with respect to  $\alpha$  Cen (Kervella et al., 2017)> no conclusive evidence for transits in MOST photometry (Kipping et al., 2017)> reduced diversity of life around M dwarfs from atmospheric erosion (Lingam & Loeb, 2017c)> planet detection by coupling VLT-SPHERE imager with ESPRESSO spectrograph (Lovis et al., 2017)> characterisation through detection of auroral emission (Luger et al., 2017b)> upper limits on mass and radius from VLT-SPHERE imaging (Mesa et al., 2017)> stellar X-ray to mid-infrared spectral energy distribution, with evidence for warm dust (Ribas et al., 2017)> atmospheric detection prospects with JWST-MIRI (Snellen et al., 2017)> hydrodynamic thermal atmospheric escape models (Zahnle & Catling, 2017)> stratospheric circulation and O<sub>3</sub> production in tidally locked planets (Carone et al., 2018)> transit search and tentative detection with BSST at Antarctica, and evidence for outer planet (Liu et al., 2018)>
- $\gamma$  Cep** proposed as a 2.7-yr period exoplanet candidate in binary system (Campbell et al., 1988)> data over 11 yr give  $P = 2.52$  yr (Walker et al., 1992)> dynamical stability (Dvorak et al., 2003a)> confirmation (Hatzes et al., 2003a)> dynamical stability (Dvorak et al., 2004a)> dynamical stability (Haghighipour, 2004)> formation (Thébaud et al., 2004)> dynamical stability of habitable zone (Haghighipour, 2006)> dynamical stability of habitable zone (Verrier & Evans, 2006)> imaging of binary companion  $\gamma$  Cep B (Neuhäuser et al., 2007a)> 3d orbit of stellar binary (Torres, 2007a)> disk truncation and planet formation (Jang-Condell et al., 2008)> planet formation in presence of disk perturbations from secondary (Kley & Nelson, 2008)> planetesimal dynamics due to gas drag from an eccentric precessing disk (Beaugé et al., 2010)> planetesimal collisions (Paardekooper & Leinhardt, 2010)> secular dynamics of planetesimals (Giuppone et al., 2011)> circumstellar disks in binary systems (Müller & Kley, 2012)> orbit properties resulting from stellar scattering (Martí & Beaugé, 2012)> planet formation in small separation binaries (Rafikov, 2013b)> application of chaos indicators (Satyal et al., 2013)> habitable terrestrial planets in tight binary systems (Funk et al., 2015)> planet formation in stellar binaries (Rafikov & Silsbee, 2015b)>
- $\tau$  Cet**  $\equiv$  HD 10700; 4-planet system (planets e, f, g, h listed in NASA); massive debris disk (Greaves et al., 2004b)> detection limits from HARPS (Dumusque et al., 2011c)> companion search with VLTI-PIONIER (Absil et al., 2011b)> proposed 5-planet system (Tuomi et al., 2013b)> high-contrast imaging characterisation (Crossfield, 2013)> Herschel observations of the debris disk (Lawler et al., 2014)> effect of chemical composition on terrestrial planets (Pagano et al., 2015)> ALMA debris disk observations (MacGregor et al., 2016a)> four planet candidates from HARPS and Keck data after removal of wavelength-dependent noise (Feng et al., 2017c)>
- 75 Cet** discovery (Sato et al., 2012b)>
- 81 Cet** discovery (Sato et al., 2008b)>
- YZ Cet** 3-planet system, with planets of  $0.002 - 0.003 M_J$  ( $0.6 - 0.9 M_\oplus$ ,

- $P_{\text{orb}} = 2 - 5$  d) orbiting a  $0.13M_{\odot}$  ( $d = 3.6$  pc) M dwarf; discovery (Astudillo-Defru et al., 2017b)>
- 7 CMa** discovery (Wittenmyer et al., 2011a)>
- $\beta$  **Cnc** discovery (Lee et al., 2014a)>
- 55 Cnc** see transiting systems
- 11 Com**  $\equiv$  HD 107383; discovery (Liu et al., 2008b)> stellar diameter and temperature (von Braun et al., 2014)>
- $\epsilon$  **CrB** discovery (Lee et al., 2012a)>
- $\kappa$  **CrB** discovery (Johnson et al., 2008a)> interferometric observations with NPOI (Baines et al., 2013)> spatially-resolved dust belts and evidence for a second planet (Bonsor et al., 2013a)>
- $\omicron$  **CrB** discovery (Sato et al., 2012b)>
- $\rho$  **CrB** 2-planet system; discovery of planet b (Noyes et al., 1997b)> stellar properties (Fuhrmann et al., 1998)> circumstellar dust disk (Trilling et al., 2000)> photometric study (Gatewood et al., 2001)> limit on  $1.6 \mu\text{m}$  flux ratio (Bender et al., 2005)> stellar diameter and temperature (von Braun et al., 2014)> discovery of planet c (Fulton et al., 2016)>
- 16 Cyg B** high eccentricity planet ( $e = 0.63$ ) around component B of a stellar binary; discovery (Cochran et al., 1997)> origin of high eccentricity (Holman et al., 1997)> Li abundance (King et al., 1997b)> origin of high eccentricity (Mazeh et al., 1997)> stellar parameters (Fuhrmann et al., 1998)> Be abundance (García Lopez & Perez de Taoro, 1998)> origin of high eccentricity (Hauser & Marcy, 1999)> Be and Fe abundances (Deliyannis et al., 2000)> Be and Fe abundances (Laws & Gonzalez, 2001)> stellar companions from imaging (Patience et al., 2002)> chemical abundances (Ramírez et al., 2011)> abundances of 16 Cyg A and B and planet formation (Schuler et al., 2011a)> asteroisemology of 16 Cyg A and B from Kepler (Metcalfe et al., 2012)> orbital analysis (Plávalová & Solovaya, 2013)> rocky core inferred from spectroscopic abundances (Tucci Maia et al., 2014)> asteroisemical inference on rotation, gyrochronology and system dynamics (Davies et al., 2015)> asteroisemology from full Kepler data (Metcalfe et al., 2015)> asteroisemology compared with Kepler Asteroisemical Legacy project (Roxburgh, 2017)>
- 18 Del** discovery (Sato et al., 2008a)> constraints on co-moving companion from Subaru-HiCIAO (Ryu et al., 2016a)>
- $\psi$  **Dra B** discovery (Endl et al., 2016)>
- 42 Dra** discovery (Döllinger et al., 2009a)> interferometry of host star (Ligi et al., 2012)>
- $\epsilon$  **Eri** dust ring (Greaves et al., 1998)> discovery, and magnetic activity cycles (Hatzes et al., 2000)> morphology of dust ring due to planet (Quillen & Thorne, 2002)> adaptive optics imaging of dust ring (Macintosh et al., 2003)> structure of dust disk due to planet and comets (Moran et al., 2004)> optical studies of disk from HST-STIS (Proffitt et al., 2004)> circumstellar dust disk from SEST-SIMBA (Schütz et al., 2004b)> debris disk structure (Greaves et al., 2005)> orbit from radial velocity and HST astrometry (Benedict et al., 2006)> differential rotation of host star from MOST and star spots (Croll et al., 2006)> rotation of the debris disk from SCUBA (Poulton et al., 2006)> null results from optical imaging (Janson et al., 2007)> optical imaging (Heinze et al., 2008)> optical imaging (Janson et al., 2008)> structure of disk due to planet (Brogi et al., 2009)> disk structure (Backman et al., 2009)> null results from imaging with Spitzer-IRAC (Marengo et al., 2009)>  $\text{H}_2\text{O}$  and silicates from disk spectral modelling (Reidemeister et al., 2011)> angular diameter of host star from NOI (Baines & Armstrong, 2012)> candidate for radio emission generated by magnetosphere-ionosphere coupling (Nichols, 2012)> magnetic activity cycle (Metcalfe et al., 2013)> extreme ultraviolet-driven mass-loss (Chadney et al., 2015)> detection of exomoons from Io-type radio emission (Noyola et al., 2014)> high-contrast imaging with Spitzer (Janson et al., 2015)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)> unsuccessful sounding rocket coronagraphic imaging mission, PICTURE-B (Chakrabarti et al., 2016)> spectroscopic and photometric stellar activity study (Giguere et al., 2016)> high-contrast imaging (Mizuki et al., 2016)> apocentre glow in eccentric debris disks (Pan et al., 2016)> northern arc of debris disk observed by ALMA has a width of 11–13 au (Booth et al., 2017a)> collisional parameters of planetesimal belt (Marzari & Dell’Oro, 2017)> inner 25 au disk resolved by SOFIA (Su et al., 2017a)> detection of  $\text{H}_2\text{O}$ -maser emission (Cosmovici & Pogrebenko, 2018)>
- $\tau$  **Gem** discovery (Mitchell et al., 2013)>
- 14 Her**  $\equiv$  HD 145675  $\equiv$  GJ 614; host star properties (Gonzalez et al., 1999)> discovery of planet b (Butler et al., 2003)> dynamical stability (Asghari et al., 2004)> evidence for planet c (Naef et al., 2004)> orbit stability (Goździewski et al., 2006)> discovery/confirmation of planet c (Wittenmyer et al., 2007)> dynamical studies (Goździewski et al., 2008b)> imaging constraints on planet c (Rodigas et al., 2011)> stellar diameter and temperature (von Braun et al., 2014)>
- $\iota$  **Hor** see HR 810
- $\gamma^1$  **Leo** discovery (Han et al., 2010)>
- $\mu$  **Leo** discovery (Lee et al., 2014a)>
- 6 Lyn** discovery (Sato et al., 2008b)>
- $\nu$  **Oct** binary star ( $P = 1050$  d,  $a = 2.6$  au) with a suggested but unconfirmed retrograde circumprimary planet ( $P = 415$  d); spectroscopic orbit from Mt John-HERCULES (Ramm et al., 2009)> stability analysis (Eberle & Cuntz, 2010)> attributed to precession in a tertiary system (Morais & Correia, 2012)> confirmed stability of retrograde orbit (Quarles et al., 2012a)> confirmed stability of retrograde orbit and problems of origin (Goździewski et al., 2013)> star spots and pulsations considered unlikely causes (Ramm, 2015)> supporting planetary evidence from 2009–13 monitoring (Ramm et al., 2016)>
- $\nu$  **Oph** 2-planet system; Lick-CAT pre-discovery monitoring (Quirrenbach et al., 2011c)> discovery of planets b and c (Sato et al., 2012b)> Bayesian analysis (Brewer & Donovan, 2015)>
- 51 Peg** first generally-accepted planet discovered around a main-sequence star; discovery (Mayor & Queloz, 1995)> orbit explained by inward migration (Lin et al., 1996)> distance and mass limits from Hipparcos astrometry (Perryman et al., 1996)> low X-ray luminosity supports planet hypothesis (Pravdo et al., 1996)> stellar parameters (Fuhrmann et al., 1997)> non-radial oscillations considered to exclude the planet hypothesis (Gray & Hatzes, 1997)> non-radial oscillations considered to exclude the planet hypothesis (Gray, 1997)> search for spectral-line shape variations (Hatzes et al., 1997)> further radial velocity measures and support for planet hypothesis (Marcy et al., 1997)> consideration of tidally-excited oscillations (Willems et al., 1997)> non-radial oscillations excluded (Brown et al., 1998b)> non-radial oscillations excluded (Brown et al., 1998a)> non-radial oscillations excluded (Gray, 1998)> non-radial oscillations excluded (Hatzes et al., 1998b)> non-radial oscillations excluded (Hatzes et al., 1998a)> non-radial oscillations excluded (François et al., 1999)> search for radio emission (Bastian et al., 2000)> transit constraints (Bundy & Marcy, 2000)> infrared constraints on transits from ISO (Rauer et al., 2000)> tidal constraints on mass (Trilling, 2000)> atmospheric modeling and tidal effects (Guillot & Showman, 2002)> atmospheric circulation and tides (Showman & Guillot, 2002)> limits on co-moving companions (Greaves, 2006)> limits on co-moving companions (Mamajek, 2010)> discovery retrospective (Mayor & Queloz, 2012)> photometric microvariability attributed to orbit perturbations (Ruban & Arkharov, 2012)> limits from 2-yr BVRI polarimetric monitoring (Antonyuk et al., 2013)> possible molecular absorption from VLT-CRIRES (Brogi et al., 2013)> simulated spectroscopic direct detection of reflected light (Martins et al., 2013)> discovery retrospective (Cenadelli & Bernagozzi, 2015)> marginal spectroscopic direct detection of reflected light (Martins et al., 2015)> reflected light not explained by ring system (Santos et al., 2015b)> discovery of atmospheric  $\text{H}_2\text{O}$  at high-spectral resolution with VLT-CRIRES (Birkby et al., 2017)>
- $\omega$  **Ser** discovery (Sato et al., 2013a)>
- 24 Sex** 2-planet system; discovery of planets b and c (Johnson et al., 2011b)> ages of resonance systems (Koriski & Zuckerman, 2011)> dynamical analysis (Wittenmyer et al., 2012b)> lucky imaging of host star (Ginski et al., 2012)> orbital evolution of a pair of giant planets in mean motion resonance (André & Papaloizou, 2016)>
- $\alpha$  **Tau** Aldebaran; discovery (Hatzes et al., 2015)> long-period radial velocity variations previously noted (Hatzes & Cochran, 1993)>
- $\epsilon$  **Tau** first open cluster planet (Hyades); discovery (Sato et al., 2007)>
- CI Tau** not in NASA; 2 Myr old classical T Tauri star with a protoplanetary disk; claimed discovery (Johns-Krull et al., 2016a)> eccentricity ( $e = 0.3$ ) excited by the disk or 2-planet scattering (Rosotti et al., 2017)> pulsed accretion (Biddle et al., 2018)>
- V830 Tau** evidence for hot Jupiter (Donati et al., 2015)> variable stellar radio emission (Bower et al., 2016)> spectropolarimetric and photometric monitoring (Donati et al., 2017)> predicted radio emission from planet and stellar wind (Vidotto & Donati, 2017)>

- o* **UMa** discovery of planet b, and evidence for planet c (Sato et al., 2012b)>
- 4 UMa** discovery (Döllinger et al., 2007)>
- 47 UMa** 3-planet system; discovery of planet b (Butler & Marcy, 1996)> distance and mass limits from Hipparcos astrometry (Perryman et al., 1996)> stellar parameters (Fuhrmann et al., 1997)> search for radio emission (Bastian et al., 2000)> discovery of planet c (Fischer et al., 2002b)> orbit stability and the habitable zone (Goździewski, 2002)> orbit stability (Jones & Sleep, 2002)> dynamical analysis (Laughlin et al., 2002)> possibility of Earth-like habitable planets (Cuntz et al., 2003)> habitable zone (Franck et al., 2003)> apsidal alignment and locking (Ji et al., 2003c)> orbit stability and habitable zone (Asghari et al., 2004)> new radial velocities (Naef et al., 2004)> similarity with solar system (Ji et al., 2005)> orbit stability (Rivera & Haghighipour, 2007)> long-period orbit fitting (Wittenmyer et al., 2007)> evidence for planet d (Gregory & Fischer, 2010)> Bayesian analysis (Feroz et al., 2011b)> mass constraints from Hipparcos (Reffert & Quirrenbach, 2011)>
- β* **UMi** discovery (Lee et al., 2014a)>
- 8 UMi** discovery (Lee et al., 2015a)>
- 11 UMi** discovery (Döllinger et al., 2009b)>
- 61 Vir** 3-planet system; discovery of planets b, c, d (Vogt et al., 2010b)> inclination constraints from tidal dissipation models (Batygin & Laughlin, 2011)> aligned major axes without tidal evolution (Greenberg & van Laerhoven, 2012)> possible radio detection with GMRT (Sirothia et al., 2014)> stellar diameter and temperature (von Braun et al., 2014)> Kuiper belt structure around nearby super-Earth hosts (Kennedy et al., 2015)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)> dynamical constraints on additional planets (Read & Wyatt, 2016)> resolved 0.86-mm debris observations with ALMA (Marino et al., 2017a)> exospheric Na escape due to stellar wind sputtering and micrometeorite impacts (Yoneda et al., 2017)>
- 70 Vir** discovery (Marcy & Butler, 1996)> distance and mass limits from Hipparcos astrometry (Perryman et al., 1996)> search for radio emission (Bastian et al., 2000)> confirmation of orbit (Naef et al., 2004)> characterisation from 59 new Keck-HIRES data with 169 previous from ELODIE, Hamilton, and HIRES (Kane et al., 2015b)>

### Star names

- Kapteyn's star** 1-planet system in NASA (planet c); discovery of planets b and c (Anglada-Escudé et al., 2014)> stellar activity as explanation for planet b (Robertson et al., 2015c)> rotation and X-ray and ultraviolet properties of host star (Guinan et al., 2016)> no activity correlation in radial velocities (Anglada-Escudé et al., 2016b)>
- Lalande 21185** not in NASA; candidate planet suggested (Butler et al., 2017)> detection of H<sub>2</sub>O-maser emission (Cosmovici & Pogrebenko, 2018)>
- Ross 128** ≡ GJ 447; nearby star (3.4 pc); discovery (Bonfils et al., 2017)>
- Wolf 1061** ≡ GJ 628; 3-planet system; discovery (Wright et al., 2016a)> further radial velocity observations (Astudillo-Defru et al., 2017c)> stellar radius from CHARA, stellar rotation from 7 yr of photometry, and no indication of transits (Kane et al., 2017b)>

### BD

- BD-06 1339** 2-planet system; discovery of planets b and c (Lo Curto et al., 2013)>
- BD-08 2823** 2-planet system; discovery of planets b and c (Hébrard et al., 2010c)>
- BD-10 3166** discovery and transit search (Butler et al., 2000)>
- BD-11 4672** discovery (Moutou et al., 2015b)>
- BD-13 2130** discovery (Lovis & Mayor, 2007)>
- BD-17 63** discovery (Moutou et al., 2009b)>
- BD+03 2562** discovery (Villaver et al., 2017)>
- BD+14 4559** discovery (Niedzielski et al., 2009b)> habitability of hypothetical exomoon (Hinkel & Kane, 2013a)>
- BD+15 2375** discovery (Niedzielski et al., 2016b)>
- BD+15 2940** planet orbiting at 0.5 au from K0 giant host, in engulfment zone; discovery (Nowak et al., 2013)>
- BD+20 274** discovery (Gettel et al., 2012a)>

- BD+20 1790** discovery (Hernán-Obispo et al., 2010)> CORALIE radial velocities imply variations are photospheric (Figueira et al., 2010a)> revised analysis supports planet interpretation (Hernán-Obispo et al., 2015)>

- BD+20 2457** 2-planet system; discovery of planets b and c (Niedzielski et al., 2009b)> dynamical investigation (Horner et al., 2014)>

- BD+48 738** discovery (Gettel et al., 2012b)>

- BD+49 828** discovery (Niedzielski et al., 2015b)>

### CoRoT

- CoRoT-7 c** see transiting systems

### GJ

- GJ 15A** discovery (Howard et al., 2014)> not confirmed by CARMENES (Trifonov et al., 2018)>

- GJ 86** discovery of planet b, and evidence for planet c (Queloz et al., 2000b)> imaging of co-moving (white dwarf/brown dwarf) companion GJ 86 B (Els et al., 2001)> orbit stability (Musielak et al., 2005)> imaging (Mugrauer et al., 2005a)> coronagraphic imaging resolves orbit motion of GJ 86 B (Lagrange et al., 2006)> stellar multiplicity (Raghavan et al., 2006)> observations with VLT-AMBER and MIDI (Matter et al., 2010)> constraints from simultaneous optical/infrared monitoring (Crockett et al., 2012)> imaging and white dwarf confirmation using HST-WFC3/STIS (Farihi et al., 2013a)> habitable terrestrial planets in tight binary systems (Funk et al., 2015)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)>

- GJ 163** 3-planet system; discovery of planets b, c, d (Bonfils et al., 2013b)> possible planet e (Tuomi & Anglada-Escudé, 2013)> variable incident flux due to obliquity and eccentricity (Kane & Torres, 2017)>

- GJ 176** see HD 285968

- GJ 179** discovery (Howard et al., 2010a)>

- GJ 221** claimed but not confirmed; 2- or 3-planet system; discovery of planets b and c (Arriagada et al., 2013); discovery of planet d (Tuomi, 2014)

- GJ 273** 2-planet system at 3.8 pc, with one in the habitable zone; discovery (Astudillo-Defru et al., 2017c)>

- GJ 317** discovery, and evidence for planet c (Johnson et al., 2007a)> mass limits from astrometry, and support for planet c (Anglada-Escudé et al., 2012b)> astrometric search with RECONS (Lurie et al., 2014)>

- GJ 328** discovery, and long-period activity cycle (Robertson et al., 2013)>

- GJ 433** 1- or 2- planet system (listed as 1-planet system in NASA); discovery of planets b and c (Delfosse et al., 2013a)> Bayesian analysis (Tuomi et al., 2014)>

- GJ 436** see transiting systems

- GJ 536** discovery (Suárez Mascareño et al., 2017a)> confirmation from CARMENES (Trifonov et al., 2018)>

- GJ 581** 3-planet system (with f, g, and possibly d subsequently questioned); M dwarf with hot Neptune (planet b), super-Earth in/near the habitable zone (c), an inner Earth-mass (e); discovery of planet b (Bonfils et al., 2005b)> transit constraints (López-Morales et al., 2006)> possibility of habitable planets (Selsis et al., 2007)> confirmation of planets c and d (Udry et al., 2007)> planet c non-habitable, planet d tidally locked near outer habitability edge (von Bloh et al., 2007a)> 3-planet system chaotic but dynamically stable (Beust et al., 2008)> discovery of inner Earth-mass planet e (Mayor et al., 2009a)> stability of undetected low-mass habitable-zone planets between planets c and d (Zollinger & Armstrong, 2009)> habitability of planet d (von Paris et al., 2010)> discovery of planet f and (habitable zone) planet g (Vogt et al., 2010a)> habitability of planet d dependent on CO<sub>2</sub> content (Wordsworth et al., 2010)> additional HARPS data does not confirm planets f and g (Forveille et al., 2011a)> Bayesian analysis (Gregory, 2011b)> habitability of planet g (Heng & Vogt, 2011)> habitability of planets c and d (Hu & Ding, 2011)> model spectra of planet d (Kaltenegger et al., 2011)> habitability of planet g (Pierrehumbert, 2011a)> tidal interactions in multi-planet systems (Papaloizou, 2011)> Bayesian analysis does not confirm planets f and g (Tuomi, 2011)> Bayesian modeling (Tuomi et al., 2011)> habitability of planet g (von Bloh et al., 2011)> atmospheric studies of



- habitability (von Paris et al., 2011b)> astrophysical parameters and habitable zone (von Braun et al., 2011a)> improved stellar parameters from interferometry, and habitability of planets d and g (von Paris et al., 2011a)> habitability of planet d (Wordsworth et al., 2011)> constraints on transits of planet e by MOST (Dragomir et al., 2012c)> spatially-resolved debris disk from Herschel-PACS (Lestrade et al., 2012)> dynamical evolution and spin-orbit resonances of planet d (Makarov et al., 2012)> dynamical stability (Tadeu dos Santos et al., 2012)> this conclusion contested (Vogt et al., 2012)> red noise questions reality of planets f, g and possibly d (Baluev, 2013f)> 3d climate modeling of close-in land planets (Lecante et al., 2013a)> model atmosphere for planet g (Carone et al., 2014)> ultraviolet radiation environment (France et al., 2013)> debris disk model (Heng & Malik, 2013)> HARPS and Keck-HIRES supports four planets (Hatzes, 2013a)> influence of thermal evolution in the magnetic protection of terrestrial planets (Zuluaga et al., 2013)> stability analysis of 4- and 5-planet systems (Joiner et al., 2014)> astrometric search with RECONS (Lurie et al., 2014)> debris disk radius and grain sizes from Herschel (Pawellek et al., 2014)> planet d an artefact of stellar activity (Robertson et al., 2014)> dynamical stability (Tóth & Nagy, 2014)> effects of activity-induced variability (Anglada-Escudé & Tuomi, 2015)> 7–15 planets suggested from Bayesian inference (Brewer & Donovan, 2015)> stellar activity as an explanation for some claimed planets (Robertson et al., 2015b)> ultraviolet flux models (Rugheimer et al., 2015b)> confirmation from CARMENES (Trifonov et al., 2018)> detection of H<sub>2</sub>O-maser emission (Cosmovici & Pogrebenko, 2018)>
- GJ 617** discovery with CARMENES (Reiners et al., 2018)>
- GJ 625** discovery (Suárez Mascareño et al., 2017b)>
- GJ 628** see Wolf 1061
- GJ 649** discovery of planet b (Johnson et al., 2010d)> high eccentricity as an artefact of unidentified multiple planets (Wittenmyer et al., 2013c)> stellar diameter and temperature (von Braun et al., 2014)>
- GJ 667C** 5-planet system; GJ 667 C is common proper motion companion to binary GJ 667 AB; discovery of planets b and c (Bonfils et al., 2013a)> 3 additional candidates from combined data (Anglada-Escudé et al., 2012a)> dynamical packing in a 6- or 7-planet system (Anglada-Escudé et al., 2013c)> effect of tidal heating on habitability (Barnes et al., 2013b)> additional HARPS data and improved orbits (Delfosse et al., 2013a)> ultraviolet radiation environment (France et al., 2013)> influence of thermal evolution in the magnetic protection of terrestrial planets (Zuluaga et al., 2013)> Bayesian analysis of radial velocity data (Feroz & Hobson, 2014)> astrometric search with RECONS (Lurie et al., 2014)> dynamical stability (Makarov & Berghea, 2014)> effects of activity-induced variability (Robertson & Mahadevan, 2014)> spin-orbit evolution (Cuartas-Restrepo et al., 2016)> stratospheric circulation and O<sub>3</sub> production in tidally locked planets (Carone et al., 2018)>
- GJ 674** discovery (Bonfils et al., 2007)> effects of stellar activity (Boisse et al., 2011)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)>
- GJ 676A** 4-planet system; discovery of planet b, and evidence for planet c (Forveille et al., 2011b)> discovery/confirmation of planet c, and suggested d and e being close-in orbits with super-Earth mass (Anglada-Escudé & Tuomi, 2012)> mass of planet b from ground-based astrometry with VLT-FORS2 (Sahlmann et al., 2016)> system is hierarchically AMD-stable (Laskar & Petit, 2017)>
- GJ 687** discovery (Burt et al., 2014)>
- GJ 785** see HD 192310
- GJ 832** 2-planet system; discovery of planet b (Bailey et al., 2009)> ultraviolet radiation environment (France et al., 2013)> discovery of planet c (Wittenmyer et al., 2014c)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)> dynamical analysis and evidence for a third planet (Satyal et al., 2017)>
- GJ 849** discovery of planet b (Butler et al., 2006a)> astrometric search with RECONS (Lurie et al., 2014)> new radial velocities (Feng et al., 2015)>
- GJ 876** 4-planet system; independent discovery of planet b (Delfosse et al., 1998)> independent discovery of planet b (Marcy et al., 1998)> constraints on debris disk (Trilling et al., 2000)> dynamical stability (Kinoshita & Nakai, 2001)> dynamical interaction between planets c and d (Laughlin & Chambers, 2001)> discovery of planet c in 2:1 resonance (Marcy et al., 2001a)> dynamical stability (Rivera & Lissauer, 2001)> disk-driven inward migration and resonant trapping (Snellgrove et al., 2001)> inclination and mass of planet b from HST-FGS (Benedict et al., 2002)> dynamical stability (Goździewski et al., 2002)> dynamical stability (Ji et al., 2002a)> dynamics and origin of the 2:1 resonance (Lee & Peale, 2002)> tidal, spin, and dynamical evolution (Mardling & Lin, 2002)> origin, evolution, and properties of resonances (Beaugé & Michtchenko, 2003)> libration (Ji et al., 2003c)> evolution of systems in resonance (Kley et al., 2004)> diversity and origin of the 2:1 resonance (Lee, 2004)> dynamical models (Kley et al., 2005)> analysis of the system (Laughlin et al., 2005a)> dynamics of 2:1 resonance systems (Psychoyos & Hadjidemetriou, 2005)> discovery of planet d, and stellar rotation (Rivera et al., 2005)> planetary migration (Beaugé et al., 2006)> constraints on transits of planets b and c (Shankland et al., 2006)> atmospheric evaporation of planet d (Lecavelier des Etangs, 2007)> orbit stability (Rivera & Haghighipour, 2007)> effect of protoplanetary disk on resonances (Veras, 2007)> improved constraints on debris disk from VLA and ACTA (Shankland et al., 2008)> mutual inclination of planets b and c from dynamics (Bean & Seifahrt, 2009)> atmospheric constraints on planet d from Spitzer-IRAC (Seager & Deming, 2009)> improved HARPS radial velocities, architecture, and constraints on putative planet e (Correia et al., 2010)> evaporation rates (Lecavelier des Etangs, 2010)> improved Keck-HIRES radial velocities, discovery of planet e in Laplace resonance (Rivera et al., 2010b)> orbit configuration (Baluev, 2011)> dynamical processes in late stages of gas and dust disks (Emelyanenko, 2011)> distinguishing true and alias periods using the Vuong test (Baluev, 2012)> time-resolved ultraviolet spectroscopy from HST-COS/STIS, and emission from hot H<sub>2</sub> (France et al., 2012)> dynamical packing (Gerlach & Haghighipour, 2012)> outward migration of a super-Earth in a disk with outward-propagating density waves (Podlęska-Gaca et al., 2012)> detectability with ELTs (Crossfield, 2013)> ultraviolet radiation environment (France et al., 2013)> stability analysis of the Laplace resonance (Martí et al., 2013)> suggestion of two additional planets from Keck/HARPS data (Jenkins et al., 2014)> no evidence of transits from Spitzer (Kammer et al., 2014)> astrometric search with RECONS (Lurie et al., 2014)> detecting exomoons from Io-type radio emission (Noyola et al., 2014)> stellar diameter and temperature (von Braun et al., 2014)> formation of multi-resonant structure with turbulent forcing (Batygin et al., 2015a)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)> simulation of Gaia astrometric data (Huang & Ji, 2016)> chaotic diffusion and orbital stability (Martí et al., 2016)> evidence for 3d Laplace resonance (Nelson et al., 2016)> formation by stellar perturbations (Shara et al., 2016)> detection of organic haze with JWST (Arney et al., 2017)> planet search utilising compressed sensing techniques (Hara et al., 2017)> astrometric planet detection with Gaia (Huang & Ji, 2017)> confirmation from CARMENES (Trifonov et al., 2018)>
- GJ 1148** = HIP 57050; 2-planet system; discovery, and location within habitable zone (Haghighipour et al., 2010)> confirmation of planet b and discovery of planet c from CARMENES (Trifonov et al., 2018)>
- GJ 3021** discovery (Naef et al., 2001b)> infrared spectra of co-moving M dwarf GJ 3021 B (Mugrauer et al., 2007)>
- GJ 3138** 3-planet system; discovery (Astudillo-Defru et al., 2017c)>
- GJ 3293** 4-planet system; discovery of planets b and c from HARPS (Astudillo-Defru et al., 2015)> discovery of planets d and e from further HARPS observations (Astudillo-Defru et al., 2017c)>
- GJ 3323** 2-planet system; discovery (Astudillo-Defru et al., 2017c)>
- GJ 3341** discovery from HARPS (Astudillo-Defru et al., 2015)>
- GJ 3470** see transiting systems
- GJ 3634** discovery, and transit search by Spitzer-IRAC (Bonfils et al., 2011)> distinguishing true and alias periods using the Vuong test (Baluev, 2012)> capture into spin-orbit resonance (Rodríguez et al., 2012)>
- GJ 3942** discovery, and possible evidence for planet c (Perger et al., 2017b)>
- GJ 3998** 2-planet super-Earth system; discovery (Affer et al., 2016)>

## HAT

- HAT-P-13 c** see transiting systems
- HAT-P-17 c** see transiting systems
- HAT-P-44 c** see transiting systems

## HD

- HD 142** 2-planet system; discovery of planet b (Tinney et al., 2002a)> discovery of planet c (Wittenmyer et al., 2012c)>
- HD 564** discovery (Moutou et al., 2015b)>
- HD 1461** 2-planet super-Earth system; discovery of planet b and evidence for two additional planets (Rivera et al., 2010a)> Spitzer transit search (Kammer et al., 2014)> stellar diameter and temperature (von Braun et al., 2014)> confirmation of planet c (Díaz et al., 2016b)>
- HD 1502** discovery (Johnson et al., 2011a)>
- HD 1605** 2-planet system; discovery (Harakawa et al., 2015)>
- HD 1666** discovery (Harakawa et al., 2015)>
- HD 1690** discovery (Moutou et al., 2011b)> limits on stellar companion (Kane et al., 2014a)>
- HD 2039** metal-enriched star; discovery (Tinney et al., 2003b)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011)>
- HD 2638** discovery (Moutou et al., 2005a)> stellar companion (Roberts et al., 2015c)> confirmed stellar companion from lucky imaging (Ginski et al., 2016a)> stellar companion (Wittrock et al., 2016)>
- HD 2952** discovery (Sato et al., 2013a)>
- HD 3651** discovery of planet b with  $e = 0.6$  (Fischer et al., 2003a)> imaging of brown dwarf companion HD 3651 B (Mugrauer et al., 2006)> infrared spectroscopy of HD 3651 B (Burgasser, 2007)> properties of the late-T dwarf companion (Liu et al., 2007b)> Bayesian analysis (Tuomi & Jones, 2012)> high eccentricity as artefact of unidentified multiple planets (Wittenmyer et al., 2013c)> long-term stability (Antoniadou & Voyatzis, 2016)>
- HD 4113** high eccentricity ( $e = 0.90$ ); discovery (Tamuz et al., 2008)>
- HD 4203** 2-planet system; discovery of planet b (Vogt et al., 2002)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011)> compositional diversity due to giant planet migration (Carter-Bond et al., 2012b)> discovery of planet c (Kane et al., 2014a)>
- HD 4208** discovery (Vogt et al., 2002)> dynamics and stability (Hinse et al., 2008)> stability of terrestrial planets in habitable zone (Alonso et al., 2009a)>
- HD 4308** discovery (Udry et al., 2006)>
- HD 4313** discovery (Johnson et al., 2010c)>
- HD 4732** 2-planet system; discovery (Sato et al., 2013b)>
- HD 5319** 2-planet system; discovery of planet b (Robinson et al., 2007b)> discovery of planet c (Giguere et al., 2015)> dynamical stability (Kane, 2016)>
- HD 5388** not in NASA; claimed discovery, unconfirmed (Santos et al., 2010b)>
- HD 5583** discovery (Niedzielski et al., 2016b)>
- HD 5608** discovery (Sato et al., 2012b)> co-moving companion from Subaru-HiCIAO (Ryu et al., 2016a)>
- HD 5891** discovery (Johnson et al., 2011a)>
- HD 6434** discovery (Mayor et al., 2004)> ephemeris refinement, transit probability, and absence of transits (Hinkel et al., 2015b)>
- HD 6718** discovery (Naef et al., 2010)>
- HD 7199** discovery, and long-term stellar activity (Dumusque et al., 2011a)>
- HD 7449** discovery of planet b, high eccentricity ( $e = 0.8$ ), and evidence for planet c (Dumusque et al., 2011a)> high eccentricity as artefact of unidentified multiple planets (Wittenmyer et al., 2013c)> long-term stability (Antoniadou & Voyatzis, 2016)> M dwarf companion from MagAO imaging (Rodigas et al., 2016)> stellar multiplicity from VLTI-SPHERE (Moutou et al., 2017)>
- HD 7924** 3-planet system; discovery of planet b (Howard et al., 2009)> no Spitzer transits (Kammer et al., 2014)> stellar diameter and temperature (von Braun et al., 2014)> discovery of planets c and d (Fulton et al., 2015b)> dynamical stability (Kane, 2016)>
- HD 8535** discovery (Naef et al., 2010)>
- HD 8574** discovery (Perrier et al., 2003)>
- HD 8673** discovery (Hartmann et al., 2010)> stellar M dwarf companion from imaging may explain high eccentricity (Roberts et al., 2015a)>
- HD 9174** discovery (Jenkins et al., 2017)>
- HD 9446** 2-planet system; discovery of planets b and c (Hébrard et al., 2010a)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)>
- HD 10180** 6-planet system (planets c–h); discovery of at least 6 planets from HARPS (Lovis et al., 2011)> tidal interactions in multi-planet systems (Papaloizou, 2011)> Bayesian analysis (Feroz et al., 2011b)> constraints on eccentricity from tidal dissipation (Laskar et al., 2012)> evidence for 9 planets in published data (Tuomi, 2012)> dynamical stability as a function of eccentricity, and planet g within habitable zone (Kane & Gelino, 2014)> planet search utilising compressed sensing techniques (Hara et al., 2017)> system is hierarchically AMD-stable (Laskar & Petit, 2017)> dynamics of possible exocomets (Loibnegger et al., 2017)> prediction of 4 missing planets from Titius–Bode law (Aschwanden, 2018)>
- HD 10442** discovery (Giguere et al., 2015)>
- HD 10647**  $\equiv \text{q}^1 \text{ Eri}$ ; unpublished discovery of planet b (quoted by Butler et al., 2006b)> planet b not confirmed (Jones et al., 2004)> planet b confirmed (Butler et al., 2006b)> infrared to sub-mm spectral energy distribution of debris disk (Liseau et al., 2008)> cold debris disk resolved by Herschel–PACS (Lineau et al., 2010)> mass constraints from Hipparcos (Reffert & Quirrenbach, 2011)> debris disk radius and grain sizes from Herschel (Pawellek et al., 2014)>
- HD 10697** discovery (Vogt et al., 2000)> Hipparcos astrometry suggests brown dwarf,  $38M_{\text{J}}$  (Zucker & Mazeh, 2000)> stellar diameter (Boyajian et al., 2013)>
- HD 11506** 2-planet system; discovery of planet b (Fischer et al., 2007a)> discovery of planet c from published data (Tuomi & Kotiranta, 2009)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)> confirmation of planet c from N2K (Giguere et al., 2015)>
- HD 11755** discovery (Lee et al., 2015a)>
- HD 11964** 2-planet system; discovery of planet b (Butler et al., 2006b)> evidence for planet d (Gregory, 2007b)> discovery of planet c (Wright et al., 2009b)> secular orbital dynamics (Veras & Ford, 2010)> tidal evolution (Correia et al., 2011)> stellar diameter (Boyajian et al., 2013)> dynamical stability (Elser et al., 2013)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)>
- HD 11977** discovery (Setiawan et al., 2005)>
- HD 12484** discovery (Hébrard et al., 2016)>
- HD 12648** discovery (Lee et al., 2015a)>
- HD 12661** 2-planet system; discovery of planet b (Fischer et al., 2001)> system stability (Kiseleva-Eggleton et al., 2002)> discovery of planet c (Fischer et al., 2003b)> system stability (Goździewski, 2003b)> system stability (Goździewski & Maciejewski, 2003)> resonant motion, and apsidal (anti-)alignment (Ji et al., 2003c)> dynamics and stability (Rodríguez & Gallardo, 2005)> orbit migration and stability (Zhang & Zhou, 2006)> proximity to resonance (Libert & Hébrard, 2007)> consistency with a stable Kozai-resonant state (Libert & Tsiganis, 2009a)> higher time-averaged eccentricity for planet c (Veras & Ford, 2009)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)>
- HD 13189** discovery (Hatzes et al., 2005)> stellar abundances (Schuler et al., 2005)>
- HD 13908** 2-planet system; discovery of planets b and c (Moutou et al., 2014b)>
- HD 13931** discovery (Howard et al., 2010a)>
- HD 14067** discovery (Wang et al., 2014c)> constraints on co-moving companion from Subaru-HiCIAO (Ryu et al., 2016a)>
- HD 16141** discovery (Marcy et al., 2000)> imaging of co-moving stellar companion (Mugrauer et al., 2005b)>
- HD 16175** discovery (Peek et al., 2009)> combined ELODIE and Lick constraints (Díaz et al., 2016a)>
- HD 16417** discovery (O’Toole et al., 2009b)>
- HD 17092** discovery (Niedzielski et al., 2007)>
- HD 17156** see transiting systems
- HD 17674** discovery (Rey et al., 2017)>
- HD 18742** discovery (Johnson et al., 2011a)>
- HD 19994** provisional discovery announced in 2000 (Queloz et al., 2004)> stellar abundances (Smith et al., 2001)> published orbit (Mayor et al., 2004)> compositional diversity due to giant planet migration (Carter-Bond et al., 2012b)> orbital analysis (Plávalová & Solovaya, 2013)> asteroseismology and impact of atomic diffusion on stellar parameters (Deal et al., 2017)>

- HD 20782** largest known eccentricity discovered by radial velocity ( $e = 0.956$ ); wide stellar binary with HD 20781; discovery (Jones et al., 2006b)> ejection of putative Earth-mass planets from habitable zone (Yeager et al., 2011)> prospects for direct imaging of tidally-powered systems (Dong et al., 2013a)> abundance analysis of wide stellar binary and evidence for planet accretion (Mack et al., 2014)> evidence for reflected light from MOST (Kane et al., 2016c)>
- HD 20794** 4-planet system; discovery of planets b, c, d (Pepe et al., 2011)> Kuiper belt structure around nearby super-Earth hosts (Kennedy et al., 2015)> discovery of planet e (Feng et al., 2017b)>
- HD 20868** discovery (Moutou et al., 2009b)>
- HD 22781** discovery (Díaz et al., 2011)> discovery (Díaz et al., 2012)>
- HD 23079** discovery (Tinney et al., 2002a)> possibility of habitable Trojans (Eberle et al., 2011)> orbit stability, and possibility of habitable exomoons (Cuntz et al., 2013)>
- HD 23127** discovery (O'Toole et al., 2007)>
- HD 23596** discovery (Perrier et al., 2003)> discovery (Udry et al., 2003b)>
- HD 24040** discovery (Wright et al., 2007)> orbit from SOPHIE, and evidence for planet c (Boisse et al., 2012b)> new radial velocities (Feng et al., 2015)>
- HD 24064** discovery (Lee et al., 2015a)>
- HD 25171** discovery (Moutou et al., 2011b)>
- HD 27442**  $\equiv \epsilon$  Ret; wide binary; discovery (Butler et al., 2001)> spectroscopy of HD 27442 B (Chauvin et al., 2007)> imaging of co-moving companion HD 27442 B (Mugrauer et al., 2007)> evolutionary constraints the white dwarf companion (Farihi et al., 2011b)> mass constraints from Hipparcos intermediate astrometry (Reffert & Quirrenbach, 2011)>
- HD 27631** discovery (Marmier et al., 2013);
- HD 27894** 3-planet system, close-in pair with 2:1 period ratio and an eccentric Jovian planet at 5.4 au; discovery of planet b (Moutou et al., 2005a)> disentangling eccentric versus 2:1 resonant radial velocity orbits, and evidence for second planet (Kürster et al., 2015)> discovery of planets b and c (Trifonov et al., 2017)>
- HD 28185** discovery (Santos et al., 2001b)> confirmation from Magellan-MIKE (Minniti et al., 2009)> habitability of hypothetical exomoon (Hinkel & Kane, 2013a)>
- HD 28254** discovery (Naef et al., 2010)>
- HD 28678** discovery (Johnson et al., 2011a)>
- HD 29021** discovery (Rey et al., 2017)>
- HD 30177** 2-planet system, metal-enriched star; discovery of planet b with AAT (Tinney et al., 2003b)> discovery of planet c with AAT (Wittenmyer et al., 2017a)>
- HD 30562** discovery (Fischer et al., 2009)>
- HD 30669** discovery (Moutou et al., 2015b)>
- HD 30856** discovery (Johnson et al., 2011a)> stellar multiplicity (Ngo et al., 2017)>
- HD 31253** discovery (Meschiari et al., 2011)>
- HD 32518** discovery (Döllinger et al., 2009b)>
- HD 32963** discovery (Rowan et al., 2016)>
- HD 33142** discovery (Johnson et al., 2011a)>
- HD 33283** discovery (Johnson et al., 2006c)> thermal detection of long-period eccentric planets during pericentre passage with Spitzer and JWST (Kane & Gelino, 2011a)>
- HD 33564** discovery (Galland et al., 2005b)> stellar diameter and temperature (von Braun et al., 2014)>
- HD 33844** 2-planet system in 3:5 resonance; discovery and dynamical stability (Wittenmyer et al., 2016c)>
- HD 34445** 6-planet system; discovery of planet b from Keck/HET (Howard et al., 2010a)> discovery of planets b–g from 18 yr of data with Keck, Magellan, APF (Vogt et al., 2017)>
- HD 35759** discovery (Hébrard et al., 2016)>
- HD 37124** 3-planet system; discovery of planet b (Vogt et al., 2000)> dynamical stability and apsidal motion (Kiseleva-Eggleton et al., 2002)> discovery of planet c (Butler et al., 2003)> dynamical stability (Goździewski, 2003a)> dynamical stability (Ji et al., 2003c)> unexpected position in HR diagram (Laws et al., 2003)> stellar models (Fernandes & Santos, 2004)> provisional discovery of planet d (Vogt et al., 2005)> dynamical stability (Goździewski et al., 2006)> dynamical stability and possible resonances (Baluev, 2008c)> dynamical stability (Goździewski et al., 2008a)> Bayesian analysis (Feroz et al., 2011b)> confirmation of planet d, and 2:1 resonance (Wright et al., 2011c)> dynamical stability (Elser et al., 2013)> reversibility error method applied to orbital dynamics (Panichi et al., 2017b)>
- HD 37605** 2-planet system; discovery of planet b with  $e = 0.7$  (Cochran et al., 2004)> persistent circumpolar vortices resulting from variable atmospheric forcing (Langton & Laughlin, 2008b)> photometric phase variations of long-period eccentric planets (Kane & Gelino, 2010)> thermal detection of long-period eccentric planets during pericentre passage with Spitzer and JWST (Kane & Gelino, 2011a)> discovery of planet c, and transit constraints on planet b (Wang et al., 2012c)> dynamics of eccentric systems (Kane & Raymond, 2014)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)>
- HD 38283** gas giant orbiting a circumpolar star with  $P = 363$  d and  $e = 0.4$ ; discovery (Tinney et al., 2011b)>
- HD 38529** 2-planet system; discovery of planet b and evidence for planet c (Fischer et al., 2001)> dynamical stability (Kiseleva-Eggleton et al., 2002)> confirmation/discovery of planet c (Fischer et al., 2003b)> dynamical stability of the habitable zone (Erdi et al., 2004)> planet c mass ( $37M_J$ ) from Hipparcos astrometry (Reffert & Quirrenbach, 2006)> proximity to resonance (Libert & Henrard, 2007)> distribution of dust-producing planetesimals from Spitzer (Moro-Martín et al., 2007)> planet c mass ( $18M_J$ ) from HST-FGS astrometry (Benedict et al., 2010)> secular orbital dynamics (Veras & Ford, 2010)> host star properties and transit exclusion (Henry et al., 2013)> collisional parameters of planetesimal belt (Marzari & Dell'Oro, 2017)>
- HD 38801** discovery (Harakawa et al., 2010)>
- HD 39091** discovery (Jones et al., 2002b)>
- HD 40307** 5-planet system; discovery of super-Earth planets b, c, d (Mayor et al., 2009b)> higher planet masses suggested by dynamical and tidal studies (Barnes et al., 2009c)> transit limits for planet b from Spitzer-IRAC (Gillon et al., 2010a)> dynamical evolution (Papaloizou & Terquem, 2010)> mean motion resonances and migration (Wang, 2011)> planets e, f, g suggested from Bayesian analysis of HARPS data (Tuomi et al., 2013a)> influence of thermal evolution in the magnetic protection of terrestrial planets (Zuluaga et al., 2013)> dynamical study of habitability of super-Earth planet g (Brasser et al., 2014)> formation of close period ratios (Chen, 2015)> gravitational quantisation of orbits (Geroyannis, 2015)> confirmation and characterisation of planets b–e (Díaz et al., 2016b)>
- HD 40956** long-period planet ( $P = 579$  d) orbiting a K giant; discovery (Jeong et al., 2018)>
- HD 40979** discovery (Fischer et al., 2003b)>
- HD 41004A** and HD 41004B hierarchical system with one planet orbiting binary component A, and a brown dwarf orbiting fainter component B; discovery of planet b orbiting HD 41004 A, and complex radial velocity signature due to proximity of binary star components (Santos et al., 2002b)> discovery of planet b orbiting HD 41004 B (Zucker et al., 2003)> nature of hierarchical system (Zucker et al., 2004)> stellar multiplicity (Raghavan et al., 2006)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011)> radial velocity contribution from tides (Arras et al., 2012)> habitable terrestrial planets in tight binary systems (Funk et al., 2015)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)> identification of secular resonances in multi-planet systems with a binary companion (Pilat-Lohinger et al., 2016)> dynamical stability (Satyal & Musielak, 2016)>
- HD 41248** not in NASA; claimed 2-planet system with periods 18.3 and 25.6 d, subsequently retracted; planet with  $P = 13.4$  d subsequently proposed; claimed discovery of planets b and c, in possible 7:5 resonance, from re-analysis of HARPS data (Jenkins et al., 2013c)> nature of the planetary signals (Jenkins & Tuomi, 2014)> signals attributed to stellar activity (Santos et al., 2014)> discovery of  $7.1M_{\oplus}$  planet with  $P = 13.4$  d (Feng et al., 2017a)>
- HD 42012** discovery (Rey et al., 2017)>
- HD 42618** discovery (Fulton et al., 2016)>
- HD 43197** discovery (Naef et al., 2010), thermal detection of long-period eccentric planets during pericentre passage with Spitzer and JWST (Kane & Gelino, 2011a)> possible radio detection with VLA NVSS (Sirothia et al., 2014)>
- HD 43691** discovery (da Silva et al., 2007)> stellar multiplicity (Ngo et al., 2017)>

- HD 44219** discovery (Naef et al., 2010)> stellar companion constraints from VLT-NACO imaging (Ginski et al., 2013)>
- HD 45350** discovery (Marcy et al., 2005b)> confirmation (Endl et al., 2006b)>
- HD 45364** 2-planet system, first discovery of a 3:2 resonance; discovery of planets b and c in 3:2 resonance (Correia et al., 2009)> possible origin of 3:2 resonance (Rein et al., 2010)> alternative formation via migration (Correia-Otto et al., 2013)> chaotically evolving eccentricities and inclinations with mutual inclinations (Barnes et al., 2015b)>
- HD 45652** discovery (Santos et al., 2008)>
- HD 46375** discovery (Marcy et al., 2000)> constraints on transits (Henry, 2000)> unexpected position in HR diagram (Laws et al., 2003)> stellar models (Fernandes & Santos, 2004)> possible detection of reflected light from CoRoT (Gaulme et al., 2010b)> spectrometry and asteroseismology (Gaulme et al., 2010a)> stellar magnetic field topology (Fares et al., 2013)> stellar wind properties, magnetic fields, bow shocks and radio emission (Vidotto et al., 2015)>
- HD 47186** 2-planet system; discovery of planets b and c (Bouchy et al., 2009)> dynamical stability of putative planet in habitable zone (Kopparapu et al., 2009)> dynamical stability (Elser et al., 2013)>
- HD 47366** not in NASA; claimed discovery of 2-planet system, possibly mutually retrograde, unconfirmed (Sato et al., 2016a)>
- HD 47536** discovery (Setiawan et al., 2003a)>
- HD 48265** discovery (Minniti et al., 2009)> improved orbit (Jenkins et al., 2017)>
- HD 49674** discovery (Butler et al., 2003)>
- HD 50499** discovery of planet b, and evidence for planet c (Vogt et al., 2005)>
- HD 50554** discovery (Fischer et al., 2002a)> orbit formalising original discovery (Perrier et al., 2003)> debris disk observations with Herschel-PACS (Dodson-Robinson et al., 2016)>
- HD 52265** discovery (Butler et al., 2000)> independent discovery (Naef et al., 2001b)> stellar composition (Santos et al., 2000a)> asteroseismology from CoRoT (Soriano et al., 2007)> asteroseismology from CoRoT (Ballot et al., 2011b)> asteroseismology from CoRoT (Escobar et al., 2012)> high eccentricity as artefact of unidentified multiple planets (Wittenmyer et al., 2013c)> seismic constraints on rotation (Gizon et al., 2013)> stellar mass and age from CoRoT asteroseismology (Lebreton & Goupil, 2014)> debris disk observations with Herschel-PACS (Dodson-Robinson et al., 2016)>
- HD 59686A** discovery (Ortiz et al., 2016)>
- HD 60532** 2-planet system; discovery of planets b and c in possible 3:1 resonance (Desort et al., 2008)> discovery and radial velocity (Desort et al., 2009a)> confirmation of the 3:1 resonance from dynamical studies, and determination of  $i = 20^\circ$  (Laskar & Correia, 2009)> origin of 3:1 resonance via resonance capture for high-mass planets (Sándor & Kley, 2010)> chaotically evolving eccentricities and inclinations with mutual inclinations (Barnes et al., 2015b)> phase space structure of the 3:1 resonance (Alves et al., 2016)> orbital evolution of a pair of giant planets in mean motion resonance (André & Papaloizou, 2016)>
- HD 62509**  $\equiv \beta$  Gem  $\equiv$  Pollux; discovery (Hatzes & Cochran, 1993)> confirmation from Lick radial velocities (Reffert et al., 2006)> planet engulfment by red giant branch evolution (Kunitomo et al., 2011)> simulation of Gaia astrometric data (Huang & Ji, 2016)> astrometric planet detection with Gaia (Huang & Ji, 2017)>
- HD 63454** discovery (Moutou et al., 2005a)> revised transit ephemeris and transit constraints (Kane et al., 2011a)> constraints on stellar variability (Kane et al., 2011a)>
- HD 63765** discovery (Ségransan et al., 2011)>
- HD 65216** 2-planet system; discovery of planets b and c (Mayor et al., 2004)> high eccentricity as artefact of unidentified multiple planets (Wittenmyer et al., 2013c)>
- HD 66141** discovery (Lee et al., 2012b)>
- HD 66428** discovery (Butler et al., 2006b)> new radial velocities (Feng et al., 2015)>
- HD 67087** 2-planet system; discovery (Harakawa et al., 2015)>
- HD 68402** discovery (Jenkins et al., 2017)>
- HD 68988** discovery (Vogt et al., 2002)> models of planet radius (Bodenheimer et al., 2003)> evidence for planet c (Wright et al., 2007)> post-Newtonian effects (Li, 2012b)> chromospheric activity (Kuznyetsova et al., 2014)>
- HD 69830** 3-planet system of Neptune masses and asteroid belt; asteroid or cometary debris from Spitzer photometry (Beichman et al., 2005a)> discovery of planets b, c, d (Lovis et al., 2006)> formation scenario via extended core accretion (Alibert et al., 2006)> system stability (Ji et al., 2007)> atmospheric evaporation (Lecavelier des Etangs, 2007)> dynamical simulations and constraints on  $e$  and  $i$  (Payne et al., 2009a)> resolved imaging of debris disk using VLT-MIDI/VISIR (Smith et al., 2009c)> limits on photometric variability of debris disk (Beichman et al., 2011)> debris disk mass estimates (Heng, 2011)> Kuiper belt structure around nearby super-Earth hosts (Kennedy et al., 2015)> stellar parameters from CHARA interferometry (Tanner et al., 2015a)> planet search utilising compressed sensing techniques (Hara et al., 2017)>
- HD 70573** discovery (Setiawan et al., 2007)>
- HD 70642** discovery (Carter et al., 2003)> dynamical stability of putative Earth-like planet in habitable zone (Hinse et al., 2008)> detection of stellar magnetic field (Fossati et al., 2013b)>
- HD 72659** discovery (Butler et al., 2003)> dynamical stability of putative Earth-like planet in habitable zone (Asghari et al., 2004)>
- HD 72892** discovery (Jenkins et al., 2017)>
- HD 73256** discovery (Udry et al., 2003a)> chromospheric activity related to stellar rotation and planet orbit (Shkolnik et al., 2005)> stellar magnetic field topology (Fares et al., 2013)> stellar wind properties, magnetic fields, bow shocks and radio emission (Vidotto et al., 2015)>
- HD 73267** discovery (Moutou et al., 2009b)>
- HD 73526** 2-planet system around metal-enriched star; discovery of planet b (Tinney et al., 2003b)> alternative orbits for planet b (Gregory, 2005)> discovery of planet c in 2:1 resonance with planet b (Tinney et al., 2006)> stability and formation of resonant system (Sándor et al., 2007a)> analysis of radial velocity variations (Pál, 2010)> stability (Zhang et al., 2010)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011b)> dynamical stability from 6 yr of radial velocities from AAT and Magellan (Wittenmyer et al., 2014b)> chaotically evolving eccentricities and inclinations with mutual inclinations (Barnes et al., 2015b)>
- HD 73534** discovery (Valenti et al., 2009)> habitability of hypothetical exomoon (Hinkel & Kane, 2013a)>
- HD 74156** 2-planet system; discovery of planets b and c (Naef et al., 2004)> dynamical stability and habitable zone (Dvorak et al., 2003b)> proximity to resonance (Libert & Henrard, 2007)> discovery of planet d (Bean et al., 2008b)> dynamical prediction of planet d (Barnes et al., 2008b)>  $^6\text{Li}/^7\text{Li}$  ratio (Ghezzi et al., 2009)> consistency with a stable Kozai-resonant state (Libert & Tsiganis, 2009a)> additional Keck-HIRES data does not confirm planet d (Meschiarri et al., 2011)> favourable for tests of solar spin-orbit coupling (Perryman & Schulze-Hartung, 2011)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)> dynamics of eccentric systems (Kane & Raymond, 2014)> new radial velocities (Feng et al., 2015)>
- HD 75289** discovery (Udry et al., 2000)> stellar abundances (Gonzalez & Laws, 2000)> stellar abundances (Santos et al., 2000a)> tidal constraints on mass of planet b (Trilling, 2000)> constraints on stellar reflected light from VLT-UVES (Leigh et al., 2003c)> imaging of co-moving stellar companion (Mugrauer et al., 2004b)> constraints on stellar reflected light from Gemini-Phoenix (Barnes et al., 2007b)> constraints on stellar reflected light (Rodler et al., 2008)> wavelength calibration using laser frequency comb (Wilken et al., 2012)>
- HD 75784** discovery (Giguere et al., 2015)>
- HD 75898** discovery (Robinson et al., 2007b)> distinguishing true and alias periods using the Vuong test (Baluev, 2012)>
- HD 76700** metal-enriched star; discovery (Tinney et al., 2003b)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011)>
- HD 76920** high eccentricity ( $e = 0.86$ ) orbiting a giant star; discovery (Wittenmyer et al., 2017b)>
- HD 77338** discovery (Jenkins et al., 2013b)> stellar abundances (Kushniruk et al., 2014)>
- HD 79498** discovery (Robertson et al., 2012a)>
- HD 80606** see transiting systems
- HD 81040** discovery (Sozzetti et al., 2006b)>
- HD 81688** discovery (Sato et al., 2008a)>
- HD 82886** discovery (Johnson et al., 2011a)>

- HD 82943** 2-planet system in 2:1 resonance; discovery of planets b and c announced in ESO press release (2001 April 4); stellar abundances (Santos et al., 2000a)> dynamical stability (Goździewski & Maciejewski, 2001)> stellar  $^6\text{Li}$  as evidence for planet engulfment (Israeli et al., 2001)> dynamical stability (Ji et al., 2002b)> search for  $^6\text{Li}$  (Reddy et al., 2002)> dynamical stability (Hadjidemetriou & Psychoyos, 2003)> measurements of  $^6\text{Li}$  (Israeli et al., 2003)> apsidal anti-alignment (Ji et al., 2003a)> dynamical stability (Ji et al., 2003c)> evolution of resonant systems (Kley et al., 2004)> orbit solution formalising original discovery (Mayor et al., 2004)> alternative orbit solutions avoiding dynamical catastrophe (Ferraz-Mello et al., 2005)> dynamical analysis (Psychoyos & Hadjidemetriou, 2005)> alternative fit to radial velocity data, based on 1:1 resonance pair (Goździewski & Konacki, 2006)> dynamical analysis (Lee et al., 2006)> dynamical analysis (Barnes & Greenberg, 2007b)> unreliability of orbit determination (Beaugé et al., 2008)>  $^6\text{Li}/^7\text{Li}$  ratio (Ghezzi et al., 2009)> photometric phase variations of long-period eccentric planets (Kane & Gelino, 2010)> constraints on location of dust-producing planetesimals (Moro-Martín et al., 2010a)> alignment of planetary orbits and debris disk (Kennedy et al., 2013)> 10-yr of Keck radial velocity data support 2:1 resonance (Tan et al., 2013)> annual CORALIE error correction, and evidence for planet d in 1:2:5 resonance (Baluev & Beaugé, 2014)> long-term stability (Antoniadou & Voyatzis, 2016)> planetary migration as the origin of the 2:1 mean motion resonance (Ramos et al., 2017)>
- HD 83443** unpublished discovery of planets b and c (see Butler et al., 2002)> stellar abundances (Santos et al., 2000a)> confirmation of planet b but not planet c (Butler et al., 2002)> tidal evolution and constraints on Love number (Wu & Goldreich, 2002)> orbit solution formalising original discovery (Mayor et al., 2004)>
- HD 85390** discovery (Mordasini et al., 2011b)> high eccentricity as artefact of unidentified multiple planets (Wittenmyer et al., 2013c)>
- HD 85512** discovery (Pepe et al., 2011)> 3d climate modeling of close-in land planets (Leconte et al., 2013a)>
- HD 86081** discovery (Johnson et al., 2006c)> stellar multiplicity (Ngo et al., 2017)>
- HD 86226** discovery (Arriagada et al., 2010)> possible radio detection with GMRT (Sirothia et al., 2014)>
- HD 86264** discovery (Fischer et al., 2009)>
- HD 86950** discovery (Wittenmyer et al., 2017c)>
- HD 87646** a giant planet (MARVELS-7 b) and a brown dwarf candidate (MARVELS-7 c) represent the first close binary with more than one substellar circumprimary companion; discovery with MARVELS (Ma et al., 2016a)>
- HD 87883** discovery (Fischer et al., 2009)>
- HD 88133** discovery (Fischer et al., 2005)> cyclic transit probabilities for long-period eccentric orbits due to apsidal precession (Kane et al., 2012b)> post-Newtonian effects (Li, 2012b)> evidence for direct detection of the thermal spectrum of the non-transiting hot gas giant (Piskorz et al., 2016)>
- HD 89307** discovery (Fischer et al., 2009)> improved orbit (Boisse et al., 2012b)>
- HD 89744** high eccentricity ( $e = 0.7$ ); discovery (Korzennik et al., 2000)> imaging of co-moving stellar companion (Mugrauer et al., 2004a)> high eccentricity as artefact of unidentified multiple planets (Wittenmyer et al., 2013c)> long-term stability (Antoniadou & Voyatzis, 2016)>
- HD 90156** discovery (Mordasini et al., 2011b)>
- HD 92788** discovery (Fischer et al., 2001)> confirmation (Mayor et al., 2004)> high eccentricity as artefact of unidentified multiple planets (Wittenmyer et al., 2013c)>
- HD 93083** discovery (Lovis et al., 2005)>
- HD 95089** discovery (Johnson et al., 2010c)>
- HD 95127** discovery (Niedzielski et al., 2015b)>
- HD 95872** discovery (Endl et al., 2016)>
- HD 96063** discovery (Johnson et al., 2011a)> 3d atmospheric circulation modeling (Medvedev et al., 2013)>
- HD 96127** discovery (Gettel et al., 2012b)>
- HD 96167** discovery (Peek et al., 2009)> high-contrast imaging search for substellar companions (Mugrauer & Ginski, 2015)>
- HD 97658** see transiting systems
- HD 98219** discovery (Johnson et al., 2011a)>
- HD 98649** high eccentricity ( $e = 0.85$ ); discovery, and uncertain origin of high eccentricity (Marmier et al., 2013)>
- HD 99109** discovery (Butler et al., 2006b)>
- HD 99492** discovery of planet b (Marcy et al., 2005b)> claimed discovery of outer planet c (Meschiari et al., 2011)> stellar activity as an explanation for claimed planet c (Kane et al., 2016b)> application of atmospheric retrieval model (Lupu et al., 2016)>
- HD 99706** discovery (Johnson et al., 2011a)>
- HD 100655** discovery (Omiya et al., 2012)>
- HD 100777** discovery (Naef et al., 2007)>
- HD 101930** discovery (Lovis et al., 2005)>
- HD 102117** discovery (Lovis et al., 2005)> independent discovery (Tinney et al., 2005)>
- HD 102195** referred to by discoverers as ET-1 (Exoplanet Tracker); discovery and confirmation with KPNO 2.1-m and HET-HRS (Ge et al., 2006)> confirmation from HARPS (Melo et al., 2007)> stellar magnetic field topology (Fares et al., 2013)> stellar wind properties, magnetic fields, bow shocks and radio emission (Vidotto et al., 2015)>
- HD 102272** 1- or 2-planet system (1 in NASA); discovery of planets b and c (Niedzielski et al., 2009a)> long-term stability (Antoniadou & Voyatzis, 2016)>
- HD 102329** discovery (Johnson et al., 2011a)>
- HD 102365** discovery (Tinney et al., 2011a)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)>
- HD 102956** discovery (Johnson et al., 2010b)>
- HD 103197** discovery (Mordasini et al., 2011b)>
- HD 103720** discovery (Moutou et al., 2015b)>
- HD 103774** discovery (Lo Curto et al., 2013)>
- HD 104067** discovery, and significant magnetic cycles (Ségransan et al., 2011)>
- HD 104985** discovery (Sato et al., 2003)>
- HD 106252** discovery (Fischer et al., 2002a)> confirmation (Perrier et al., 2003)>
- HD 106270** discovery (Johnson et al., 2011a)>
- HD 106515A** discovery (Desidera et al., 2012)> improved orbit (Marmier et al., 2013)> binary star dynamics (Rica et al., 2017)>
- HD 107148** discovery (Butler et al., 2006b)> wide white dwarf companion from imaging, HD 107148B (Mugrauer et al., 2014b)> spectroscopy of HD 107148B (Mugrauer & Dinçel, 2016)>
- HD 108147** discovery (Pepe et al., 2002)> cyclic transit probabilities for long-period eccentric orbits due to apsidal precession (Kane et al., 2012b)>
- HD 108341** high eccentricity ( $e = 0.85$ ); discovery (Moutou et al., 2015b)>
- HD 108863** discovery (Johnson et al., 2011a)>
- HD 108874** 2-planet system; discovery of planet b (Butler et al., 2003)> discovery of planet c (Vogt et al., 2005)> dynamical stability and proximity to 4:1 resonance (Goździewski et al., 2006)> dynamical stability (Libert & Henrard, 2007)> stable orbits for Trojan terrestrial planets in habitable zone (Schwarz et al., 2007a)> secular orbital dynamics (Veras & Ford, 2010)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)> three year monitoring and improved orbits from HARPS-N (Benatti et al., 2017)>
- HD 109246** discovery (Boisse et al., 2010)>
- HD 109271** 2-planet system; discovery of planets b and c (Lo Curto et al., 2013)>
- HD 109749** discovery (Fischer et al., 2006)>
- HD 110014** discovery (de Medeiros et al., 2009)>
- HD 111232** discovery (Mayor et al., 2004)> confirmation (Minniti et al., 2009)>
- HD 111591** long-period planet ( $P = 1056$  d) orbiting a K giant; discovery (Jeong et al., 2018)>
- HD 111998** discovery (Borgniet et al., 2017)>
- HD 113337** discovery (Borgniet et al., 2014)>
- HD 113538** 2-planet system; discovery of planets b and c (Moutou et al., 2011b)> orbit update (Moutou et al., 2015b)>
- HD 113996** long-period planet ( $P = 610$  d) orbiting a K giant; discovery (Jeong et al., 2018)>

- HD 114386** 1- or 2-planet system (listed as 1-planet system in NASA) discovery of planet b and unconfirmed planet c (Udry et al., 2003b)> discovery from CORALIE (Mayor et al., 2004)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011)>
- HD 114613** discovery (Wittenmyer et al., 2014a)>
- HD 114729** discovery (Butler et al., 2003)> imaging of co-moving stellar companion (Mugrauer et al., 2005b)> possible additional planets (Goździewski & Migaszewski, 2006)>
- HD 114762** discovery, probable brown dwarf (Latham et al., 1989)> non-detection of transits (Robinson et al., 1990)> confirmation of discovery orbit (Cochran et al., 1991)> radio emission (Bastian et al., 2000)> co-moving companion (Patience et al., 2002)> limits on radio emission (Farrell et al., 2004a)> revised orbit and transit constraints (Kane et al., 2011c)> inclination effect on phase variations (Kane & Gelino, 2012a)>
- HD 114783** discovery (Vogt et al., 2002)>
- HD 116029** discovery (Johnson et al., 2011a)> stellar multiplicity (Ngo et al., 2017)>
- HD 117207** discovery (Marcy et al., 2005b)> detection of stellar magnetic field (Fossati et al., 2013b)>
- HD 117618** discovery (Tinney et al., 2005)> high eccentricity as an artefact of unidentified multiple planets (Wittenmyer et al., 2013c)>
- HD 118203** discovery (da Silva et al., 2006)>
- HD 120084** discovery (Sato et al., 2013a)>
- HD 121056** not in NASA; claimed 2-planet system from AAT observations (Wittenmyer et al., 2015)>
- HD 121504** discovery (Mayor et al., 2004)>
- HD 125595** discovery (Ségransan et al., 2011)>
- HD 125612** 3-planet system; discovery of planet b (Fischer et al., 2007a)> imaging of co-moving companion (Mugrauer & Neuhauser, 2009)> discovery of planets c and d (Lo Curto et al., 2010)> super-Earth architecture explained by outer giant planet scattering (Huang et al., 2017b)>
- HD 126614** discovery (Howard et al., 2010a)>
- HD 128311** 2-planet system; discovery of planet b (Butler et al., 2003)> discovery of planet c in possible 2:1 resonance (Vogt et al., 2005)> alternative fit based on 1:1 resonance pair (Goździewski & Konacki, 2006)> dynamical evolution and migration (Sándor & Kley, 2006)> constraints on dust-producing planetesimals (Moro-Martín et al., 2010a)> dynamical evolution (Zhang et al., 2010)> analysis of radial velocity variations (Pál, 2010)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)> HST-FGS astrometry providing inclination, but not supporting resonance (McArthur et al., 2014)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)> reanalysis of radial velocity data and stability analysis (Rein, 2015)>
- HD 128356** discovery (Jenkins et al., 2017)>
- HD 129445** discovery (Arriagada et al., 2010)>
- HD 130322** discovery (Udry et al., 2000)> stellar magnetic field topology (Fares et al., 2013)> revised orbit new photometry and radial velocities, transit constraints, rotation from star spots (Hinkel et al., 2015a)> stellar wind properties, magnetic fields, bow shocks and radio emission (Vidotto et al., 2015)>
- HD 131496** discovery (Johnson et al., 2011a)>
- HD 131664** brown dwarf of  $18-23M_J$ ; discovery (Moutou et al., 2009b)> mass constrained by Hipparcos astrometry (Sozzetti & Desidera, 2010)> habitable zone (Kane & Gelino, 2012b)>
- HD 132406** discovery (da Silva et al., 2007)>
- HD 132563B** planet orbiting one component of hierarchical triple system; discovery (Desidera et al., 2011)>
- HD 133131A** and **HD 133131B** G2+G2 'twin' binary, 360 au separation, with 2 planets around A, and one around B; discovery (Teske et al., 2016b)>
- HD 134987** 2-planet system; discovery of planet b (Vogt et al., 2000)> updated orbit (Butler et al., 2006b)> discovery of planet c (Jones et al., 2010b)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)>
- HD 136418** discovery (Johnson et al., 2010c)>
- HD 137388A** discovery, and long-term stellar activity (Dumusque et al., 2011a)>
- HD 139357** discovery (Döllinger et al., 2009a)>
- HD 141399** 4-planet system; discovery, one of the first with APF (Vogt et al., 2014a)> improved orbit constraints (Hébrard et al., 2016)> system is hierarchically AMD-stable (Laskar & Petit, 2017)>
- HD 141937** discovery (Udry et al., 2002)>
- HD 142022A** high-eccentricity ( $e = 0.53$ ) long-period ( $P \sim 5$  yr) planet in wide binary; discovery (Eggenberger et al., 2006)>
- HD 142245** discovery (Johnson et al., 2011a)> high-contrast imaging search for substellar companions (Mugrauer & Ginski, 2015)>
- HD 142415** discovery (Mayor et al., 2004)>
- HD 143105** discovery (Hébrard et al., 2016)>
- HD 143361** discovery (Minniti et al., 2009)> additional observations (Jenkins et al., 2017)>
- HD 145377** discovery (Moutou et al., 2009b)>
- HD 145457** discovery (Sato et al., 2010)>
- HD 145934** discovery (Feng et al., 2015)>
- HD 147018** 2-planet system; discovery of planets b and c (Ségransan et al., 2010)> dynamical stability (Elser et al., 2013)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)>
- HD 147513** discovery (Udry et al., 2003b)> discovery (Mayor et al., 2004)> possible additional planets (Goździewski & Migaszewski, 2006)>  $^6\text{Li}/^7\text{Li}$  ratio (Ghezzi et al., 2009)> mass constraints from Hipparcos (Reffert & Quirrenbach, 2011)> stability of possible Trojan planets in habitable zone (Funk et al., 2012)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)> coronal structure (Alvarado-Gómez et al., 2016a)> stellar wind and coronal heating (Alvarado-Gómez et al., 2016b)> spectropolarimetric study of host star (Hussain et al., 2016)>
- HD 147873** 2-planet system; discovery (Jenkins et al., 2017)>
- HD 148156** discovery (Naef et al., 2010)>
- HD 148427** discovery (Fischer et al., 2009)>
- HD 149026** see transiting systems
- HD 149143** discovery (Fischer et al., 2006)> confirmation (da Silva et al., 2006)>
- HD 150706** discovery (Udry et al., 2003b)> published orbit (Boisse et al., 2012b)>
- HD 152079** discovery (Arriagada et al., 2010)> additional observations (Jenkins et al., 2017)>
- HD 152581** discovery (Johnson et al., 2011a)>
- HD 153950** discovery (Moutou et al., 2009b)>
- HD 154345** discovery (Wright et al., 2007)> Jupiter-like planet and 9-yr stellar activity cycle (Wright et al., 2008)> improved orbit (Boisse et al., 2012b)>
- HD 154672** discovery (López-Morales et al., 2008)> additional observations (Jenkins et al., 2017)>
- HD 154857** 2-planet system; discovery of planet b, and evidence for planet c (McCarthy et al., 2004)> evidence for planet c (O'Toole et al., 2007)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011)> confirmation of planet c (Wittenmyer et al., 2014a)>
- HD 155233** discovery (Wittenmyer et al., 2016b)>
- HD 155358** 2-planet system around low-metallicity star ( $[\text{Fe}/\text{H}] = -0.68$ ); discovery of planets b and c (Cochran et al., 2007)> consistency with a stable Kozai-resonant state (Libert & Tsiganis, 2009a)> analysis of radial velocity variations (Pál, 2010)> revised analysis using EXOFT (Balan & Lahav, 2011)> revised period for planet c, indicating 2:1 resonance (Robertson et al., 2012a)> 3d atmospheric circulation modeling (Medvedev et al., 2013)> orbital evolution of a pair of giant planets in mean motion resonance (André & Papaloizou, 2016)> orbital configuration and conditions for mean motion resonance (Ma et al., 2017)> resonant structure, formation, and stability (Silburt & Rein, 2017)>
- HD 156279** discovery (Díaz et al., 2012)>
- HD 156411** discovery (Naef et al., 2010)> thermal detection of long-period eccentric planets during pericentre passage with Spitzer and JWST (Kane & Gelino, 2011a)>
- HD 156668** discovery (Howard et al., 2011a)> distinguishing true and alias periods using the Vuong test (Baluev, 2012)> no evidence of transits from Spitzer (Kammer et al., 2014)>

- HD 156846** high eccentricity ( $e = 0.85$ ); discovery (Tamuz et al., 2008)> orbit from photometry and Keck-HIRES monitoring (Kane et al., 2011d)> thermal detection of long-period eccentric planets during pericentre passage with Spitzer and JWST (Kane & Gelino, 2011a)>
- HD 158038** discovery (Johnson et al., 2011a)>
- HD 159243** 2-planet system; discovery (Moutou et al., 2014b)>
- HD 159868** 2-planet system; discovery of planet b (O'Toole et al., 2007)> discovery of planet c, and revised orbit for planet b (Wittenmyer et al., 2012c)>
- HD 160691** see  $\mu$  Ara
- HD 162020** discovery (Udry et al., 2002)> constraints on radio emission from GMRT (Winterhalter et al., 2005)> inclination effect on phase variations (Kane & Gelino, 2012a)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)>
- HD 163607** 2-planet system, planet b of high eccentricity ( $e = 0.7$ ); discovery of planets b and c (Giguere et al., 2012)> dynamical stability (Elser et al., 2013)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)> dynamics of eccentric systems (Kane & Raymond, 2014)>
- HD 164509** discovery of planet b, and evidence for planet c (Giguere et al., 2012)> possible radio detection with GMRT (Sirothia et al., 2014)> new stellar companion from Gemini-DSSI (Wittrock et al., 2016) stellar multiplicity (Ngo et al., 2017)>
- HD 164595** discovery (Courcol et al., 2015)>
- HD 164604** discovery (Arriagada et al., 2010)>
- HD 164922** 2-planet system; discovery of planet b (Butler et al., 2006b)> discovery of planet c (Fulton et al., 2016)>
- HD 165155** discovery (Jenkins et al., 2017)>
- HD 166724** single massive planet of high eccentricity ( $e = 0.7$ ); discovery (Marmier et al., 2013)>
- HD 167042** discovery (Johnson et al., 2008a)> confirmation (Sato et al., 2008b)>
- HD 168443** 2-planet system; discovery of planet b (Marcy et al., 1999)> discovery of planet c (Marcy et al., 2001b)> confirmation (Udry et al., 2002)> dynamical stability of habitable zone (Érdi et al., 2004)> planet b mass ( $34M_J$ ) from Hipparcos astrometry (Reffert & Quirrenbach, 2006)> proximity to resonance (Libert & Henrard, 2007)> secular orbital dynamics (Veras & Ford, 2010)> favourable for tests of solar spin-orbit coupling (Perryman & Schulze-Hartung, 2011)> absence of non-grazing transit for planet b (Pilyavsky et al., 2011)> dynamical stability (Elser et al., 2013)> dynamics of eccentric systems (Kane & Raymond, 2014)> limits on stellar companions to host stars with eccentric planets (Kane et al., 2014a)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)>
- HD 168746** discovery (Pepe et al., 2002)> models of planet radius (Bodenheimer et al., 2003)> post-Newtonian effects (Li, 2012b)> chromospheric activity (Kuznyetsova et al., 2014)>
- HD 169830** 2-planet system; stellar abundances (Santos et al., 2000a)> discovery of planet b (Naef et al., 2001b)> dynamical stability of habitable zone (Érdi et al., 2004)> dynamical stability (Goździewski & Konacki, 2004)> discovery of planet c (Mayor et al., 2004)> proximity to resonance (Libert & Henrard, 2007)> consistency with a stable Kozai-resonant state (Libert & Tsiganis, 2009a)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)>
- HD 170469** discovery (Fischer et al., 2007a)>
- HD 171028** discovery (Santos et al., 2007)> further observations with HARPS (Santos et al., 2011)>
- HD 171238** discovery (Ségransan et al., 2010)>
- HD 173416** discovery (Liu et al., 2009)>
- HD 175167** discovery (Arriagada et al., 2010)>
- HIP 175370** unconfirmed (not in NASA); discovery (Hrudková et al., 2017)>
- HD 175541** discovery (Johnson et al., 2007b)>
- HD 175607** discovery (Mortier et al., 2016)>
- HD 176986** 2-planet system; discovery (Suárez Mascareño et al., 2018)>
- HD 177565** discovery (Feng et al., 2017a)>
- HD 177830** 2-planet system; discovery of planet b (Vogt et al., 2000)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011)> improved orbit, and planet c (Meschiarri et al., 2011)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)> distant stellar companion not affecting dynamical evolution (Roberts et al., 2015b)>
- HD 178911B** host star is distant component of hierarchical triple system; discovery (Zucker et al., 2002)>
- HD 179079** discovery (Valenti et al., 2009)>
- HD 179949** discovery (Tinney et al., 2001)> planet-induced chromospheric activity (Shkolnik et al., 2003)> orbit dependence of chromospheric activity and magnetic interaction (Shkolnik et al., 2005)> constraints on radio emission from GMRT (Winterhalter et al., 2005)> magnetic communication (Preusse et al., 2006)> constraints on atmospheric TiO and VO from VLT-CRIRES (Barnes et al., 2008a)> enhanced stellar magnetic activity due to close-in planet (Lanza, 2008)> planet-induced stellar X-ray activity from Chandra-ACIS-S (Saar et al., 2008)> magnetic interaction with host star (Kopp et al., 2011)> stellar magnetic field, differential rotation and chromospheric activity (Fares et al., 2012)> planet-induced emission due to star-planet interaction (Gurdemir et al., 2012)> stellar magnetic field topology (Fares et al., 2013)> simultaneous optical and X-ray spectroscopy disfavours star-planet interaction (Scandariato et al., 2013)> magnetic energy fluxes in sub-Alfvén planet-star and moon-planet interactions (Saur et al., 2013)> atmospheric CO and H<sub>2</sub>O for non-transiting planet from VLT-CRIRES (Brogi et al., 2014)> time scales of radio emission variability (See et al., 2015)> stellar wind properties, magnetic fields, bow shocks and radio emission (Vidotto et al., 2015)> 3d atmospheric modeling and light curve (Jiménez-Torres, 2016)>
- HD 180314** discovery (Sato et al., 2010)>
- HD 180902** discovery (Johnson et al., 2010c)>
- HD 181342** discovery (Johnson et al., 2010c)>
- HD 181433** 3-planet system, all with high eccentricities; discovery of planets b, c, d (Bouchy et al., 2009)> revised orbits based on dynamic stability, with planets c and d in 5:2 resonance (Campanella, 2011)> eccentricities excited by ejection of additional giant planet (Campanella et al., 2013)>
- HD 181720** discovery (Santos et al., 2010b)> further observations with HARPS (Santos et al., 2011)>
- HD 183263** 2-planet system; discovery of planet b (Marcy et al., 2005b)> discovery of planet c (Wright et al., 2009b)> secular evolution in second-order Hamiltonian expansion (Libert & Sansottera, 2013)> new radial velocities (Feng et al., 2015)>
- HD 185269** high-eccentricity ( $e = 0.3$ ) hot Jupiter; discovery (Johnson et al., 2006b)> independent discovery (Moutou et al., 2006)>
- HD 187085** high-eccentricity 1000-d orbit; discovery (Jones et al., 2006b)>
- HD 187123** 2-planet system; discovery of planet b (Butler et al., 1998)> stellar abundances (Gonzalez et al., 1999)> tidal constraints on mass (Trilling, 2000)> indication of planet c (Vogt et al., 2000)> orbit confirmation (Naef et al., 2004)> confirmation of planet c (Wright et al., 2007)> dynamical stability (Elser et al., 2013)> new radial velocities (Feng et al., 2015)>
- HD 188015** discovery (Marcy et al., 2005b)> possible additional planets (Goździewski & Migaszewski, 2006)> ejection of putative Earth-mass planets from habitable zone (Yeager et al., 2011)>
- HD 189733** see transiting systems
- HD 190360** 2-planet system; discovery of planet b (Naef et al., 2003)> discovery of planet b (Udry et al., 2003b)> discovery of planet c (Vogt et al., 2005)> possible additional planets (Goździewski & Migaszewski, 2006)> proximity to resonance (Libert & Henrard, 2007)> secular orbital dynamics (Veras & Ford, 2010)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011)> cyclic transit probabilities for long-period eccentric orbits due to apsidal precession (Kane et al., 2012b)> dynamical stability (Elser et al., 2013)>
- HD 190647** discovery (Naef et al., 2007)>
- HD 190984** discovery (Santos et al., 2010b)> further observations with HARPS (Santos et al., 2011)>
- HD 191806** discovery (Díaz et al., 2016a)>
- HD 192263** discovery (Santos et al., 2000b)> independent discovery (Vogt et al., 2000)> planet falsely attributed to stellar variability (Henry et al., 2002)> planet confirmation (Santos et al., 2003b)> confirmation, stellar rotation, spots, and transit constraints (Dragomir et al., 2012a)>
- HD 192310** = GJ 785; 2-planet system; discovery of planet b (Howard et al., 2011b)> discovery of planet c (Pepe et al., 2011)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)>

- HD 192699** discovery (Johnson et al., 2007b)>
- HD 195019** star is component of binary system; discovery (Fischer et al., 1999)> updated orbit (Vogt et al., 2000)> stability of orbits in binary systems (Musielak et al., 2005)>
- HD 196050** discovery (Jones et al., 2002a)> independent discovery (Udry et al., 2003b)> independent discovery (Mayor et al., 2004)> imaging of co-moving stellar companion (Mugrauer et al., 2005b)>
- HD 196067** discovery (Marmier et al., 2013)>
- HD 196885A** discovery, and orbit constraints for HD 196885 B (Correia et al., 2008b)> spectroscopy of HD 196885 B (Chauvin et al., 2007)> independent confirmation (Fischer et al., 2009)> co-moving nature and orbit curvature of HD 196885 B (Chauvin et al., 2011)> formation in accretion-hostile regions of binary systems (Thébault, 2011)> dynamical analysis (Giuppone et al., 2012b)> planet formation in small separation binaries (Rafikov, 2013b)> application of chaos indicators (Satyal et al., 2013)> chaotic and quasi-periodic phase space regions from MEGNO (Satyal et al., 2014)> habitable terrestrial planets in tight binary systems (Funk et al., 2015)> orbital dynamics and Lyapunov time (Melnikov, 2017)>
- HD 197037** discovery (Robertson et al., 2012a)> stellar companion from lucky imaging (Ginski et al., 2016a)>
- HD 200964** 2-planet system; discovery of planets b and c, and proximity to a 4:3 resonance (Johnson et al., 2011b)> difficulty explaining 4:3 mean motion resonance (Rein et al., 2012)> stability and characterisation of 4:3 resonance (Wittenmyer et al., 2012b)> formation and evolution of 4:3 resonant system (Tadeu dos Santos et al., 2015)> orbital dynamics (Mia & Kushvah, 2016)>
- HD 202206** 2-planet system orbiting a face-on G+M binary; inner is massive, outer less massive; stellar abundances (Santos et al., 2000a)> discovery of planet b, possible planet c, and possible formation scenarios (Udry et al., 2002)> discovery of planet c, in 5:1 resonance (Correia et al., 2005)> dynamical stability, and sensitivity to mutual inclinations (Goździewski et al., 2006)> dynamical stability (Libert & Henrard, 2007)> dynamical stability (Couetdic et al., 2010)> constraints on location of dust-producing planetesimals (Moro-Martín et al., 2010a)> astrometric modeling with HST-FGS (Benedict & Harrison, 2017)>
- HD 204313** 2- or 3-planet system (listed as 2-planet system in NASA); discovery of planet b (Ségransan et al., 2010)> discovery of planet c (Mayor et al., 2011)> proposed planet d, in 3:2 resonance with planet b (Robertson et al., 2012b)> confirmation and characterisation of planets b–c (Díaz et al., 2016b)>
- HD 204941** discovery, and long-term stellar activity (Dumusque et al., 2011a)>
- HD 205739** discovery (López-Morales et al., 2008)>
- HD 206610** discovery (Johnson et al., 2010c)>
- HD 207832** 2-planet system; discovery of planets b and c (Haghighipour et al., 2012)> stellar multiplicity (Ngo et al., 2017)>
- HD 208487** 1- or 2-planet system (listed as 1-planet system in NASA); discovery of planet b (Tinney et al., 2005)> possible additional planets (Goździewski & Migaszewski, 2006)> proposed planet c (Gregory, 2007a)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011)>
- HD 208527** planet orbiting M giant; discovery (Lee et al., 2013a)>
- HD 208897** discovery (Yılmaz et al., 2017)>
- HD 209458** see transiting systems
- HD 210277** discovery (Marcy et al., 1999)> stellar abundances (Gonzalez et al., 1999)> detection of debris disk with IRTF–CoCo (Trilling et al., 2000)> stability of possible Trojan planets in habitable zone (Funk et al., 2012)>
- HD 210702** discovery (Johnson et al., 2007b)> stellar diameter and temperature (von Braun et al., 2014)>
- HD 212301** discovery (Lo Curto et al., 2006)> imaging of co-moving companion (Mugrauer & Neuhäuser, 2009)>
- HD 212771** discovery (Johnson et al., 2010c)> K2 asteroseismology and mass determination (Campante et al., 2017)>
- HD 213240** discovery (Santos et al., 2001b)> imaging of co-moving stellar companion (Mugrauer et al., 2005b)> compositional diversity due to giant planet migration (Carter-Bond et al., 2012b)>
- HD 214823** discovery (Díaz et al., 2016a)>
- HD 215497** 2-planet system; discovery of planets b and c (Lo Curto et al., 2010)>
- HD 216435**  $\equiv \tau^1$  Gru; discovery (Jones et al., 2003)>
- HD 216437** discovery (Jones et al., 2002a)> independent discovery (Udry et al., 2003b)> independent discovery (Mayor et al., 2004)>
- HD 216536** discovery (Niedzielski et al., 2015b)>
- HD 216770** discovery (Mayor et al., 2004)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011)>
- HD 217107** 2-planet system; discovery of planet b (Fischer et al., 1999)> tidal constraints on mass (Trilling, 2000)> updated orbit (Vogt et al., 2000)> models of planet radius (Bodenheimer et al., 2003)> discovery of planet c, and transit constraints (Vogt et al., 2005)> dynamical stability (Libert & Henrard, 2007)>  $^6\text{Li}/^7\text{Li}$  ratio (Ghezzi et al., 2009)> search for infrared emission with Gemini–Phoenix (Cubillos et al., 2011)> Bayesian modeling (Tuomi et al., 2011)> post-Newtonian effects (Li, 2012b)> stellar diameter (Boyajian et al., 2013)> dynamical stability (Elser et al., 2013)> new radial velocities (Feng et al., 2015)>
- HD 217786** discovery (Moutou et al., 2011b)> stellar companion from lucky imaging (Ginski et al., 2016a)>
- HD 218566** discovery (Meschiari et al., 2011)>
- HD 219077** discovery, and high eccentricity (0.77) (Marmier et al., 2013)>
- HD 219134** see transiting systems
- HD 219415** discovery (Gettel et al., 2012a)>
- HD 219828** 2-planet system; discovery of planet b, and evidence for planet c (Melo et al., 2007)> chromospheric activity (Kuznyetsova et al., 2014)> confirmation of planet c (Santos et al., 2016)>
- HD 220074** planet orbiting an M giant; discovery (Lee et al., 2013a)>
- HD 220689** discovery (Marmier et al., 2013)>
- HD 220773** discovery (Robertson et al., 2012a)>
- HD 220842** discovery (Hébrard et al., 2016)>
- HD 221287** discovery (Naef et al., 2007)>
- HD 221585** discovery (Díaz et al., 2016a)>
- HD 222076** discovery (Wittenmyer et al., 2017c)>
- HD 222155** discovery of planet b, and suggestion of planet c (Boisse et al., 2012b)>
- HD 222582** discovery (Vogt et al., 2000)>
- HD 224538** discovery (Jenkins et al., 2017)>
- HD 224693** discovery (Johnson et al., 2006c)>
- HD 231701** discovery (Fischer et al., 2007a)>
- HD 233604** planet orbiting at 0.75 au from K5 giant host, in engulfment zone; discovery (Nowak et al., 2013)>
- HD 240210** discovery of planet b, and evidence for others (Niedzielski et al., 2009b)>
- HD 240237** discovery (Gettel et al., 2012b)>
- HD 285507** first (eccentric) hot Jupiter in the Hyades open cluster; discovery (Quinn et al., 2014)>
- HD 285968**  $\equiv$  GJ 176; discovery ( $P = 10.2$  d) (Endl et al., 2008b)>  $P = 10.2$  d confirmed (Butler et al., 2009)> alternative fit to  $P = 8.8$  d (Forveille et al., 2009)> stellar diameter and temperature (von Braun et al., 2014)> effects of stellar activity on radial velocity signal for M dwarfs (Robertson et al., 2015a)> confirmation from CARMENES (Trifonov et al., 2018)>
- HD 290327** discovery (Naef et al., 2010)>
- HD 330075** discovery (Pepe et al., 2004a)> measurement of  $^9\text{Be}$  depletion (Delgado Mena et al., 2011)>

## HIP (Hipparcos)

- HIP 5158** 2-planet system; discovery of planets b and c (Lo Curto et al., 2010)> confirmation of planets b and c (Feroz et al., 2011a)>
- HIP 8541** discovery (Jones et al., 2016b)>
- HIP 11915** not in NASA; unconfirmed Jupiter twin around a solar twin (Bedell et al., 2015)>
- HIP 11952** retracted system around a metal-poor star; claimed discovery of 2-planet system from FEROS (Setiawan et al., 2012)> unconfirmed by HARPS/HARPS-N (Desidera et al., 2013)> re-analysis of FEROS data invalidates original claim (Müller et al., 2013a)>
- HIP 12961** discovery (Forveille et al., 2011b)>
- HIP 13044** not in NASA archive after planet's existence was questioned in 2014; suggested planet orbiting a metal-poor red horizontal branch star; discovery from FEROS (Setiawan et al., 2010)> radial velocity contribution from tides (Arras et al., 2012)> survival models (Passy et al., 2012)> origin of planet orbit (Bear et al., 2011b)> origin of planet orbit (Tutukov & Fedorova, 2013)> reanalysis of FEROS data does not confirm planet's existence (Jones & Jenkins, 2014)>



**HIP 14810** 3-planet system; discovery of planet b (Butler et al., 2006b)> independent discovery of planet b, and discovery of planet c (Wright et al., 2007)> discovery of planet d (Wright et al., 2009a)> dynamical stability (Elser et al., 2013)> hot Jupiter migration attributed to disk interactions (Wang et al., 2017d)>

**HIP 57274** 3-planet system; discovery of planets b, c, d (Fischer et al., 2012a)> dynamical stability (Elser et al., 2013)> no evidence of transits from Spitzer (Kammer et al., 2014)>

**HIP 63242** discovery (Jones et al., 2013b)>

**HIP 65407** 2-planet system; discovery (Hébrard et al., 2016)>

**HIP 65891** discovery (Jones et al., 2015b)>

**HIP 67537** high-eccentricity planet at the planet/brown-dwarf boundary ( $e = 0.59$ ,  $M_p \sin i = 11.1 M_J$ ); discovery from CHIRON/FEROS (Jones et al., 2017)>

**HIP 67851** 2-planet system; discovery (Jones et al., 2015a)> confirmation of planet c (Jones et al., 2015b)>

**HIP 70849** discovery (Ségransan et al., 2011)>

**HIP 74890** discovery (Jones et al., 2016b)>

**HIP 75458**  $\equiv \iota$  Dra; discovery (Frink et al., 2002)> effect of stellar pulsations (Hekker et al., 2006a)> favourable transit potential (Kane et al., 2010)> mass constraints from Hipparcos (Reffert & Quirrenbach, 2011)> stellar parameters from CHARA interferometry (Baines et al., 2011)>

**HIP 79431** discovery (Apps et al., 2010)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)>

**HIP 91258** discovery (Moutou et al., 2014b)>

**HIP 97233** discovery (Jones et al., 2015a)>

**HIP 105854** discovery (Jones et al., 2014)>

**HIP 107773** discovery (Jones et al., 2015b)>

**HIP 109384** discovery (Hébrard et al., 2016)>

**HIP 109600** discovery (Hébrard et al., 2016)>

### HR

**HR 228** see HD 4732

**HR 810**  $\equiv \iota$  Hor  $\equiv$  HD 17051; discovery (Kürster et al., 2000)> asteroseismology and fundamental star parameters (Laymand & Vauclair, 2007)> an evaporated member of the primordial Hyades cluster (Vauclair et al., 2008)> 1.6 year stellar magnetic activity cycle (Metcalfe et al., 2010)> effects of stellar activity (Boisse et al., 2011)>

### KELT

**KELT-6 c** see transiting systems

### Kepler

**Kepler-19 d** see transiting systems

**Kepler-20 g** see transiting systems

**Kepler-25 d** see transiting systems

**Kepler-48 e** see transiting systems

**Kepler-56 d** see transiting systems

**Kepler-68 d** see transiting systems

**Kepler-93 c** see transiting systems

**Kepler-94 c** see transiting systems

**Kepler-97 c** see transiting systems

**Kepler-407 c** see transiting systems

**Kepler-424 c** see transiting systems

**Kepler-432 c** see transiting systems

**Kepler-454 c** see transiting systems

### NGC

**NGC 2682 Sand 364** member of open cluster NGC 2682 (M67); discovery (Brucalassi et al., 2014)>

**NGC 2682 Sand 978** member of open cluster NGC 2682 (M67); discovery (Brucalassi et al., 2017)>

**NGC 2682 YBP 401** member of open cluster NGC 2682 (M67); discovery (Brucalassi et al., 2016b)>

**NGC 2682 YBP 1194** member of open cluster NGC 2682 (M67); discovery (Brucalassi et al., 2014)>

**NGC 2682 YBP 1514** member of open cluster NGC 2682 (M67); discovery (Brucalassi et al., 2014)>

**NGC 2423 3** not in NASA; member of open cluster NGC 2423; claimed discovery (Lovis & Mayor, 2007)>

**NGC 4349 127** member of open cluster NGC 4349; discovery (Lovis & Mayor, 2007)>

### Pr (Praesepe)

**Pr 201**  $\equiv$  BD+20 2184; member of open cluster Praesepe (M44); discovery (Quinn et al., 2012b)> stellar rotation (Kovács et al., 2014)>

**Pr 211** 2-planet system; member of open cluster Praesepe (M44); discovery of planet b (Quinn et al., 2012b)> stellar rotation (Kovács et al., 2014)> discovery of planet c (Malavolta et al., 2016)>

### TAP

**TAP 26** discovery using Zeeman-Doppler imaging (Yu et al., 2017)>

### TYC (Hipparcos/Tycho)

**TYC 1240-945-1** retracted system (MARVELS-1); originally reported as a  $28 M_J$  companion in a  $P = 5.9$  d,  $e \sim 0$  orbit (Lee et al., 2011b)> subsequently reclassified as a face-on stellar binary in a 3-4 star system (Wright et al., 2013)>

**TYC 1422-614-1** 2-planet system; discovery of planets b and c (Niedzielski et al., 2015a)>

**TYC 3667-1280-1** massive red giant ( $M_* = 1.9 M_\odot$ ) hosting a warm Jupiter ( $a = 0.21$  au,  $M_p \sin i = 5.4 M_J$ ); discovery from HET-HRS and HARPS-N (Niedzielski et al., 2016c)>

**TYC 4282-605-1** discovery (González-Álvarez et al., 2017)>

### WASP

**WASP-8 c** see transiting systems

**WASP-41 c** see transiting systems

**WASP-47 c** see transiting systems

**WASP-94B c** see transiting systems

### XO

**XO-2S b,c** see transiting systems



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# Appendix D. Transiting exoplanets

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This appendix includes objects appearing in the online NASA Exoplanet Archive as of 31 December 2017, along with a small number of other candidates or retracted systems.

These notes list some key attributes of the system to underline its particular interest, give some indication of the attention the object has received (through the length of the bibliography), and provide a concise note on each paper to serve as a guide to the literature and a narrative of the progress in understanding the system. It makes no claim for completeness, and CDS–SIMBAD should be consulted for more details.

It includes only cross-identifications which are relevant in context, e.g., as used in the early discovery literature. CDS–SIMBAD or the NASA Exoplanet Archive should be consulted for other aliases. If a different alias was used in the NASA archive, this is explicitly noted.

Of the confirmed Kepler–NNN systems, the NASA Exoplanet Archive retains the KIC number as default identifier for 7, and the KOI number as default for 9. The listing here is according to the Kepler identifier.

The electronic version includes three classes of hyperlink: the object identifier (in bold) is linked to the host star page of the NASA Exoplanet Archive (it will be invalid if their syntax changes); each citation is linked to the bibliography; and the ▷ icon following the citation links to the relevant ADS page.

The word ‘discovery’ is used to characterise the leading reference for brevity although, for some of the Kepler transits, a more appropriate term would be discovery and/or confirmation of previously identified candidates.

**Independent discoveries:** For independent discoveries, the first reported is considered the ‘primary’ identifier:

primary:	secondary:
HAT–P–7	≡ Kepler–2
HAT–P–11	≡ Kepler–3
HAT–P–14	≡ WASP–27
HAT–P–27	≡ WASP–40
HAT–P–30	≡ WASP–51
HAT–P–56	≡ K2–20
KELT–14	≡ WASP–122
KELT–20	≡ MASCARA–2
K2–29	≡ WASP–152
TRAPPIST–1	≡ K2–112
TrES–2	≡ Kepler–1
WASP–11	≡ HAT–P–10
WASP–28	≡ K2–1
WASP–47	≡ K2–23
WASP–75	≡ K2–40
WASP–85A	≡ K2–94
WASP–151	≡ K2–134
WASP–157	≡ K2–41
WASP–167	≡ KELT–13

**Systems discovered by radial velocity**, but with one planet (indicated) which also transits. All references to the system are included here:

30 Ari B	planet b
55 Cnc	planet e
GJ 436	planet b
GJ 3470	planet b
HD 17156	planet b
HD 80606	planet b
HD 97658	planet b
HD 149026	planet b
HD 189733	planet b
HD 209458	planet b
HD 219134	planets b and c

**Systems discovered by transit photometry**, with additional planet(s) discovered through radial velocity measures. All references to the system are included here:

CoRoT–7	planet c
HAT–P–13	planet c
HAT–P–17	planet c
HAT–P–44	planet c
KELT–6	planet c
Kepler–19	planet d
Kepler–20	planet g
Kepler–25	planet d
Kepler–48	planet e
Kepler–56	planet d
Kepler–68	planet d
Kepler–93	planet c
Kepler–94	planet c
Kepler–97	planet c
Kepler–407	planet c
Kepler–424	planet c
Kepler–432	planet c
Kepler–454	planet c
K2–18	planet c
K2–96	planet d
WASP–8	planet c
WASP–41	planet c
WASP–47	planet c
WASP–94B	planet b
XO–2S	planets b and c

## Notes on individual systems

## A. Radial velocity discoveries, subsequently found to transit

- 30 Ari B** planet orbits one component of (2+2) quadruple stellar system; discovered by radial velocity (Guenther et al., 2009) > transits identified *a posteriori* in Hipparcos photometry (Kane et al., 2015a) > fourth stellar component (Roberts et al., 2015c) > secular dynamics modeled with the `SecularMultiple` nested binary algorithm (Hamers & Portegies Zwart, 2016a) >
- 55 Cnc** = HR 3522; 5-planet system, discovered by radial velocity, of which only planet e transits; discovery of planet b by radial velocity, evidence for planet c (Butler et al., 1997) > stellar properties (Balunas et al., 1997) > circumstellar Vega-like disk from ISO (Dominik et al., 1998) > stellar parameters (Fuhrmann et al., 1998) > Be depletion in host star (García López & Pérez de Taoro, 1998) > stellar parameters,  $T_{\text{eff}}$ ,  $\log g$ , [Fe/H] (Gonzalez & Vanture, 1998) > circumstellar Vega-like disk from infrared coronagraphy (Trilling & Brown, 1998) > limits on radio emission from VLA (Bastian et al., 2000) > imaging of circumstellar disk (Trilling et al., 2000) > disk not verified with HST-NICMOS coronagraphy (Schneider et al., 2001) > disk not verified with JCMT-SCUBA (Jayawardhana et al., 2002) > mass constraints from HST-FGS astrometry (McGrath et al., 2002) > discovery of planets c and d (Marcy et al., 2002) > planets b and c in 3:1 resonance (Ji et al., 2003b) > habitability and orbit stability of Earth-type planets (von Bloh et al., 2003b) > models of resonant capture within protoplanetary disk (Kley et al., 2004) > discovery of planet e (McArthur et al., 2004) > radial velocity observations with ELODIE (Naef et al., 2004) > 3:1 resonance stability (Marzari et al., 2005) > resonance migration (Beaugé et al., 2006) > (a)symmetric 3:1 resonances (Voyatzis & Hadjidemetriou, 2006) > 3:1 resonance stability (Barnes & Greenberg, 2007b) > evaporation of planet e, pre-discovery as transiting (Lecavelier des Etangs, 2007) > stability of test particles (Rivera & Haghighipour, 2007) > confirmation of planets c and d, and discovery of planet f (Fischer et al., 2008) > chaotic stability (Gayon et al., 2008) > Titius-Bode law and prediction of planet g (Poveda & Lara, 2008) > system stability (Raymond et al., 2008b) > planets b and c not in resonance (Voyatzis, 2008) > limits on polarised light (Lucas et al., 2009) > period ambiguity of planet d and revised period for planet e (Dawson & Fabrycky, 2010) > drag-induced resonant capture in a multi-planet scenario (de la Fuente Marcos & de la Fuente Marcos, 2010) > effects of magnetic drag and Ohmic dissipation (Castan & Menou, 2011) > detection of planet e transits with Spitzer (Demory et al., 2011a) > dynamical stability, coplanar orbits probably inclined with respect to stellar equator (Kaib et al., 2011b) > atmospheric modeling of planet e from photometric phase curves (Kane et al., 2011b) > stellar properties and improved radius for planet e from interferometry (von Braun et al., 2011b) > detection of planet e transits with MOST (Winn et al., 2011c) > distinguishing between true and alias periods using the Vuong test (Baluev, 2012) > elliptical instability of planet e due to tides, precession/nutation, and libration (Cebron et al., 2012) > brightness temperature of planet e from stellar calibration (Crossfield, 2012) > Titius-Bode law (Cuntz, 2012) > wavelength-dependent astrometric motion (Coughlin & López-Morales, 2012b) > detection of planet e transits with Spitzer (Demory et al., 2012) > extended atmosphere of planet e from HST-STIS and Chandra (Ehrenreich et al., 2012a) > mass of planet e from improved radial velocity (Endl et al., 2012) > improved radius of planet e from Spitzer/MOST (Gillon et al., 2012a) > atmospheric stability under tidal locking (Heng & Kopparla, 2012) > C-rich interior of planet e from structure models (Madhusudhan et al., 2012) > capture into spin-orbit resonance (Rodríguez et al., 2012) > dynamical modeling (Van Laerhoven & Greenberg, 2012) > tidal dissipation and eccentricity pumping of planet e (Bolmont et al., 2013) > chaotic rotation around synchronous state driven by tidal torque and asymmetric figure (Callegari & Rodríguez, 2013) > hydrodynamic blow-off of atmospheric H (Lammer et al., 2013b) > simulated direct detection of reflected light of planet e via high-resolution spectroscopy (Martins et al., 2013) > host star C/O abundance (Teske et al., 2013a) > Rossiter-McLaughlin effect of planet e from HARPS-N at  $0.6 \text{ m s}^{-1}$  indicates prograde polar orbit (Bourrier & Hébrard, 2014) > ground-based transit detections of planet e with NOT-ALFOSC (de Mooij et al., 2014) > MOST photometry (Dragomir et al., 2014) >  $\text{C}_2\text{H}_2$  at 1.0–1.5 and 9–14  $\mu\text{m}$  as a diagnostic for hydrocarbon-rich atmospheres (Hu & Seager, 2014) > no Rossiter-McLaughlin effect for planet e from HARPS-N at  $0.35 \text{ m s}^{-1}$  (López-Morales et al., 2014) > N-body constraints and dynamical analysis (Nelson et al., 2014b) > Doppler noise and 13-yr activity cycle (Baluev, 2015a) > tidal evolution and passage through secular resonances (Hansen & Zink, 2015) > measures for characterising  $\text{H}_2\text{O}$ -rich super-Earths (Madhusudhan & Redfield, 2015) > gyrochronology and isochrone ages (Maxted et al., 2015b) > constraining the volatile fraction from transit observations (Alibert, 2016) > map of the large day-night temperature gradient (Demory et al., 2016b) > variability in dayside thermal emission (Demory et al., 2016b) > favourable for lightning-discharge studies during transit (Hodosán et al., 2016a) > exosphere transit models compared with solar data from SDO (Llama & Shkolnik, 2016) > limits on Na and Ca from transmission spectrum with VLT-UVES, HARPS/HARPS-N (Ridden-Harper et al., 2016) > possible HCN detection from HST-WFC3 (Tsiaras et al., 2016a) > Spitzer phase curve favours an atmosphere (Angelo & Hu, 2017) > Bayesian analysis of interior structure using stellar abundance proxies (Dorn et al., 2017a) > limits on  $\text{H}_2\text{O}$ -vapour from Subaru-HDS and CFHT-ESPaDOns (Esteves et al., 2017) > linking the climate and thermal phase curve (Hammond & Pierrehumbert, 2017) > planet search utilising compressed sensing techniques (Hara et al., 2017) > system is hierarchically AMD-stable (Laskar & Petit, 2017) > probable formation of planet e from  $\text{H}_2\text{O}$ -poor material within the snow line (Lopez, 2017) > cloud formation in metal-rich atmospheres (Mahapatra et al., 2017) > improved ground-based transit photometry using beam-shaping diffusers (Stefansson et al., 2017) > prediction of 7 missing planets from Titius-Bode law (Aschwanden, 2018) >
- GJ 436** M dwarf with one confirmed Neptune-mass planet (of high eccentricity) and two unconfirmed planets; radial velocity discovery with Keck-HIRES, and absence of photometric variability (Butler et al., 2004b) > secondary eclipse and orbit from Spitzer-IRAC, possible planet c (Deming et al., 2007a) > characterisation with Spitzer and ground-based observations (Demory et al., 2007) > optical transit detected at 0.6-m OFXB, and constraints on composition ( $\text{H}_2\text{O}$ -ice+H/He layer) (Gillon et al., 2007b) > transit detection of planet b with Spitzer-IRAC (Gillon et al., 2007a) > composition from evaporation status (Lecavelier des Etangs, 2007) > parameters from stellar modeling (Maness et al., 2007) > parameters from stellar modeling (Torres, 2007b) > second planet unconfirmed by photometry (Alonso et al., 2008b) > transit photometry with HST-FGS (Bean et al., 2008a) > proposed orbit model for planet c considered implausible (Bean & Seifahrt, 2008) > trend in transit parameters from ground photometry support planet c (Coughlin et al., 2008) > planet c inferred from perturbed orbit of (near-grazing incidence) planet b, explaining large  $e$  (Ribas et al., 2008) > homogeneous analysis and light curve properties (Southworth, 2008) > second planet hypothesised to maintain eccentricity (Batygin et al., 2009b) > limits on transit time variations (Cáceres et al., 2009) > composition modeling (Figueira et al., 2009) > constraints on Trojan companions (Madhusudhan & Winn, 2009) > improved transit photometry from HST-NICMOS and limits on transit time variations (Pont et al., 2009a) > homogeneous analysis: physical properties (Southworth, 2009) > EPOXI photometry transit limits of planet c, and star spots (Ballard et al., 2010b) > search for planetary companions (Ballard et al., 2010a) > atmospheric circulation models (Lewis et al., 2010) > composition modeling (Nettelmann et al., 2010) > interior composition (Rogers & Seager, 2010a) > homogeneous analysis: additional planets and stellar models (Southworth, 2010) > atmospheric modeling of  $\text{CO}/\text{CH}_4/\text{H}_2\text{O}/\text{CO}_2$  from Spitzer secondary eclipse (Stevenson et al., 2010) >  $\text{CH}_4$  inferred from multi-wavelength photometry (Beaulieu et al., 2011) > heavy-element composition of disk-instability planets (Boley et al., 2011) > atmospheric  $\text{CH}_4$  (Beaulieu et al., 2011) > models of thermal phase variations for eccentric orbits (Cowan & Agol, 2011a) > outlier in heat redistribution attributed to eccentric orbit (Cowan & Agol, 2011b) > exospheric Ly $\alpha$  absorption from HST-STIS (Ehrenreich et al., 2011b) > absence of molecular features from HST-NICMOS re-analysis (Gibson et al., 2011b) > modeling of tidal Love number (Kramm et al., 2011) > stellar variability and dayside flux variations (Knutson et al., 2011) >  $\text{CH}_4$  abundance under ultraviolet irradiation (Line et al., 2011) > atmospheric modeling from Spitzer: non-equilibrium chemistry (Madhusudhan & Seager, 2011) > secondary eclipse modeling with JWST predictions (Shabram et al., 2011) > Rossiter-McLaughlin effect from Magellan, Keck, effect of star-planet tidal interactions on obliquities (Albrecht et al., 2012b) > Kozai resonance as an explanation for high eccentricity of planet b (Beust et al., 2012) > wavelength-dependent astrometric motion (Coughlin & López-Morales, 2012b) > atmospheric stability under tidal locking (Heng & Kopparla, 2012) > post-Newtonian effects (Li, 2012b) > two additional transiting plan-

- ets (c and d) suggested from Spitzer (Stevenson et al., 2012b)> stellar diameter from CHARA (von Braun et al., 2012)> ultraviolet radiation environment (France et al., 2013)> atmospheric disequilibrium diagnostics and C/O (Line & Yung, 2013)> atmospheric composition as a function of temperature, metallicity and C/O ratio (Moses et al., 2013b)> Doppler signatures of atmospheric circulation (Showman et al., 2013a)> models favour high metallicity, high CO/CH<sub>4</sub> ratio, and efficient tidal heating (Agúndez et al., 2014b)> extended Ly- $\alpha$  transit from HST-STIS suggests comet-like tail (Kulow et al., 2014)> featureless transmission spectrum ruling out cloud-free, H-dominated atmosphere (Knutson et al., 2014a)> systematic atmospheric retrieval analysis (Line et al., 2014)> metal-rich atmosphere depleted in CH<sub>4</sub> and enhanced in CO/CO<sub>2</sub> (Lanotte et al., 2014)> orbital dynamics and prediction of transit time variations for planet c (Maciejewski et al., 2014a)> no sub-Earth transiting companion from HST-WFC3 (Stevenson et al., 2014a)> location in Spitzer 3.6/4.5  $\mu$ m colour-magnitude diagram (Triaud, 2014)> compilation of light curves and transit timing (Baluev et al., 2015)> low CH<sub>4</sub>/CO<sub>2</sub> ratio from carbonaceous refractory matter by impacting micrometeorites (Dangi et al., 2015)> giant comet-like cloud of escaping H (Ehrenreich et al., 2015)> He atmospheres (Hu et al., 2015b)> revisiting Spitzer transit observations (Morello et al., 2015)> effect of Ly- $\alpha$  radiation on mini-Neptune atmospheres around M stars (Miguel et al., 2015)> stellar wind interactions from HST-STIS (Bourrier et al., 2016)> extreme ultraviolet flux and the escaping atmosphere (Guo & Ben-Jaffel, 2016)> exosphere transit models compared with solar data from SDO (Llama & Shkolnik, 2016)> atmospheric escape of hot gas coupling plasma, photoionisation and Ly- $\alpha$  emission (Salz et al., 2016)> no asymmetry in ground-based ultraviolet transits (Turner et al., 2016b)> search for H $\alpha$  absorption (Cauley et al., 2017b)> extended egress over 10–25 h in Ly- $\alpha$  from HST-STIS (Lavie et al., 2017a)> forward and inverse modeling of the emission and transmission spectrum (Morley et al., 2017a)> ultraviolet C II and Si III transit spectroscopy with HST-COS (Parke Loyd et al., 2017)> confirmation from CARMENES (Trifonov et al., 2018)> probe of host star wind (Vidotto & Bourrier, 2017)> HST-STIS transit spectrum from 0.53–1.03  $\mu$ m (Lothringer et al., 2018)>
- GJ 3470** discovered by radial velocity (ESO-HARPS), with transits from ESO-TRAPPIST (Bonfils et al., 2012)> flat atmospheric transmission spectrum from Keck-MOSFIRE (Crossfield et al., 2013)> transit photometry and secondary eclipse from Spitzer-IRAC (Demory et al., 2013b)> cloud-free atmosphere from optical to near-infrared transit with Okayama (Fukui et al., 2013)> atmospheric scattering from ultraviolet and near infrared transits with LBT (Nascimbeni et al., 2013b)> revised star and planet parameters from optical to near-infrared transits (Biddle et al., 2014)> flat transmission spectrum from 1–5  $\mu$ m from HST-WFC3 (Ehrenreich et al., 2014)> metallicity and temperature effects on CH<sub>4</sub>/CO (Venot et al., 2014)> atmospheric Rayleigh scattering (Dragomir et al., 2015)> transit timing variation and transmission spectroscopy (Awiphan et al., 2016a)> atmospheric escape coupling plasma, photoionisation and Ly- $\alpha$  emission (Salz et al., 2016)> spectrally resolved Rayleigh scattering slope from GTC-OSIRIS (Chen et al., 2017a)>
- HD 17156** long-period (21.2 d) and high eccentricity ( $e = 0.67$ ); discovery from radial velocity with N2K-Subaru (Fischer et al., 2007a)> transits detected (Barbieri et al., 2007)> Rossiter-McLaughlin effect (Cochran et al., 2008)> improved transit photometry (Gillon et al., 2008)> theoretical infrared light curves (Irwin et al., 2008a)> Rossiter-McLaughlin effect from OAO-HIDES, later superseded (Narita et al., 2008)> transits and Rossiter-McLaughlin effect from TNG-SARG (Barbieri et al., 2009)> atmospheric modeling (Koskinen et al., 2009)> Rossiter-McLaughlin effect from Subaru-HDS (Narita et al., 2009a)> transit measurements and prediction of secondary eclipse (Winn et al., 2009b)> time-dependent atmospheric model for eccentric orbits (Iro & Deming, 2010)> models of thermal phase variations for eccentric orbits (Cowan & Agol, 2011a)> asteroseismology from HST-FGS (Gilliland et al., 2011b)> transits from HST-FGS (Nutzman et al., 2011b)> photometry and new spectroscopy (Southworth, 2011)> eccentricity from photo-eccentric effect (Dawson & Johnson, 2012)> asteroseismology and age determination (Lebreton, 2012)> favourable for polarisation studies (Wiktorowicz & Laughlin, 2014)> optical and X-ray observations of star-planet interaction (Maggio et al., 2015)>
- HD 80606** planet orbits one component of wide (2000 au) binary, high eccentricity ( $e = 0.933$ ), and transits host star over  $\sim 12$  h; radial velocity discovery and high eccentricity (Naef et al., 2001a)> planet orbit may originate from Kozai resonance/migration (Wu & Murray, 2003)> detection by UCL observatory (Fossey et al., 2009)> detection by Esteve Duran observatory (García-Melendo & McCullough, 2009)> detection of secondary eclipse from Spitzer and planet heating from pericentre photometry (Laughlin et al., 2009)> independent transit detection by three groups: OHP/SOPHIE (Moutou et al., 2009a)> Rossiter-McLaughlin effect (Pont et al., 2009b)> orbit constraints from transit ingress (Winn et al., 2009c)> transit observations with Spitzer and SOPHIE (Hébrard et al., 2010b)> multi-site transit coverage (Hidas et al., 2010)> full 12-hr transit observed by Spitzer and OHP-SOPHIE (Hébrard et al., 2010b)> time-dependent atmospheric model for eccentric orbits (Iro & Deming, 2010)> constraints on radio emission at pericentre from VLA (Lazio et al., 2010b)> multi-site transit coverage (Shporer et al., 2010b)> transit time variations in eccentric hierarchical triple systems, Kozai cycles and tidal friction (Borkovits et al., 2011)> tidal evolution (Correia et al., 2011)> models of thermal phase variations for eccentric orbits (Cowan & Agol, 2011a)> outlier in heat redistribution attributed to eccentric orbit (Cowan & Agol, 2011b)> photometry and new spectroscopy (Southworth, 2011)> limits on atmospheric K (Colón et al., 2012b)> habitable zone for eccentric orbits (Kane & Gelino, 2012b)> 12-hr transit observed by MOST (Roberts et al., 2013a)> superrotating atmosphere in cyclostrophic balance (Peralta et al., 2014a)> polarisation with POLISH-2 (Wiktorowicz & Laughlin, 2014)> atmospheric radiative and dynamical time scales from periastron passage observations with Spitzer (de Wit et al., 2016a)> no evidence for star-planet interaction at pericentre passage (Figueira et al., 2016b)> detailed chemical abundances from Keck-HIRES (Mack et al., 2016)> formation by stellar perturbations (Shara et al., 2016)>
- HD 97658** radial velocity discovery with Keck-HIRES (Howard et al., 2011b)> transit detection, unpublished (Henry et al., 2011a)> transit not confirmed by MOST (Dragomir et al., 2012b)> transit detection by MOST (Dragomir et al., 2013)> C<sub>2</sub>H<sub>2</sub> at 1.0–1.5 and 9–14  $\mu$ m as diagnostic for hydrocarbon-rich atmospheres (Hu & Seager, 2014)> transmission spectrum from HST-WFC3 (Knutson et al., 2014b)> orbit parameters versus atmospheric species (Miguel & Kaltenegger, 2014)> transit confirmation from Spitzer (Van Grootel et al., 2014)> limits on H-exosphere from HST-STIS, Chandra and XMM-Newton (Bourrier et al., 2017d)> Bayesian analysis of interior structure using stellar abundance proxies (Dorn et al., 2017a)>
- HD 149026** small hot Saturn-mass (0.37 M<sub>J</sub>) planet; radial velocity discovery with N2K-Subaru, transit detection, heavy element core (Sato et al., 2005a)> constraints on Li and K (Bozorgnia et al., 2006)> transits and heavy core (Charbonneau et al., 2006)> atmosphere and interior models (Fortney et al., 2006b)> possible origin of the massive core (Ikoma et al., 2006)> possible origin of the massive core (Broeg & Wuchterl, 2007)> secondary eclipse and high brightness temperature (Harrington et al., 2007)> Rossiter-McLaughlin effect (Wolf et al., 2007)> homogeneous analysis and light curve properties (Southworth, 2008)> 5 transits from Fairborn (Winn et al., 2008a)> 4 near infrared transits from HST-NICMOS (Carter et al., 2009)> formation and migration (Dodson-Robinson & Bodenheimer, 2009)> secondary eclipse depth and infrared phase variations from Spitzer-IRAC (Knutson et al., 2009b)> radius from Spitzer transits (Nutzman et al., 2009)> homogeneous analysis: physical properties (Southworth, 2009)> homogeneous analysis and light curve properties (Southworth, 2010)> heavy-element composition of disk-instability planets (Boley et al., 2011)> alkali line absorption in Na I and KI (Jensen et al., 2011)> 3 transits and 11 secondary eclipses from Spitzer favour high CO and CO<sub>2</sub> (Stevenson et al., 2012a)> atmospheric disequilibrium diagnostics (Line & Yung, 2013)> atmospheric heat redistribution efficiency drops as stellar insolation rises (Perez-Becker & Showman, 2013)> systematic atmospheric retrieval analysis (Line et al., 2014)> constraints on Bond albedo and day-night heat transport from secondary eclipse depths (Schwartz & Cowan, 2015)> phase curves and albedo from Spitzer photometry (Zhang et al., 2018a)>
- HD 189733** 1.1 M<sub>J</sub> planet orbiting nearby (19 pc) K0 star at  $a = 0.03$  au, host star is primary of a binary system, secondary is an M dwarf at 216 au; radial velocity discovery with OHP-ELODIE, and transit discovery (Bouchy et al., 2005c)> identification of secondary M dwarf at 216 au (Bakos et al., 2006b)> multicolour photometry, transit parameters (Bakos et al., 2006a)> prominent secondary eclipse from Spitzer (Deming et al., 2006)> *a posteriori* transit detection in Hipparcos photometry (Hébrard & Lecavelier des Etangs, 2006)> Rossiter-McLaughlin effect ( $\lambda = -1.4^\circ$ ) from Keck-HIRES (Winn et al., 2006b)>

stellar angular diameter from CHARA ( $R = 1.2R_J$  and  $\rho = 0.9 \text{ Mg m}^{-3}$ ) (Baines et al., 2007)> limits on H<sub>2</sub>O and CO absorption at 2.0–2.4  $\mu\text{m}$  from Keck–NIRSPEC (Barnes et al., 2007a)> transit detection limits of 2 $R_p$  from 21 d of MOST (Croll et al., 2007b)> limits on atmospheric H<sub>2</sub>O from Spitzer–IRAC (Ehrenreich et al., 2007)> flat atmospheric spectrum (7.5–14.7  $\mu\text{m}$ ) from Spitzer (Grillmair et al., 2007)> energy redistribution from irradiated day-side (Knutson et al., 2007a)> strong complex stellar magnetic field from Zeeman signature in CFHT–ESPaDOnS polarimetry (Moutou et al., 2007b)> star spots, with no evidence for satellites or rings from HST–ACS (Pont et al., 2007a)> H<sub>2</sub>O absorption (Tinetti et al., 2007b)> quasi-periodic flux variations with 13.4 d period attributed to stellar rotation (Winn et al., 2007c)> polarised scattered light of amplitude  $2 \times 10^{-4}$  (Berdyugina et al., 2008)> H<sub>2</sub>O detection and circulation models from Spitzer (Barman, 2008)> transits at 3.6 and 5.8  $\mu\text{m}$  with Spitzer–IRAC suggest sub-micron particle haze (Beaulieu et al., 2008)> two secondary eclipses from Spitzer show 4  $\mu\text{m}$  opacity and no temperature inversion (Charbonneau et al., 2008)> strong H<sub>2</sub>O absorption in day-side emission spectrum (Grillmair et al., 2008)> host star rotation period  $P = 11.953 \pm 0.009 \text{ d}$  (Henry & Winn, 2008)> enhanced stellar magnetic activity due to close-in planet (Lanza, 2008)> Rayleigh scattering by MgSiO<sub>3</sub> (0.55–1.05  $\mu\text{m}$ ) gives  $T_{\text{atm}} = 1340 \text{ K}$  (Lecavelier des Etangs et al., 2008a)> 10 transits over 21 d by MOST and limits on transit time variations (Miller-Ricci et al., 2008a)> featureless transmission spectrum from HST–ACS (Pont et al., 2008a)> Na I doublet absorption with HET–HRS (Redfield et al., 2008)> H<sub>2</sub>O and CH<sub>4</sub> absorption from secondary eclipse with HST–NICMOS (Swain et al., 2008b)> 3d simulations of atmospheric circulation (Showman et al., 2008a)> linear polarisation attributed to thin cloud of sub- $\mu\text{m}$  dust grains (Sengupta, 2008)> homogeneous analysis and light curve properties (Southworth, 2008)> stellar activity and stellar rotation from OHP–SOPHIE (Boisse et al., 2009)> constraints on CO from Spitzer–IRAC (Désert et al., 2009)> constraints on day-night circulation from Spitzer–MIPS at 24  $\mu\text{m}$  (Knutson et al., 2009c)> limits on radio emission at 244 and 614 MHz from GMRT (Lecavelier des Etangs et al., 2009)> abundances and minimum mass of heavy elements (Mousis et al., 2009)> homogeneous analysis: physical properties (Southworth, 2009)> Rayleigh scattering by sub-micron haze particles with no H<sub>2</sub>O from HST–NICMOS (Sing et al., 2009)> H<sub>2</sub>O, CO, CO<sub>2</sub> required to explain near-infrared day-side spectrum from HST–NICMOS (Swain et al., 2009c)> 3d simulations coupling atmospheric dynamics to cloud-free radiative transfer (Showman et al., 2009)> limits on 307–347 MHz radio emission during secondary eclipse from NRAO (Smith et al., 2009b)> Rossiter–McLaughlin effect from ESO–HARPS (Triaud et al., 2009)> non-detection of polarised scattered light from POLISH (Wiktorowicz, 2009)> atmospheric modeling from six transits and six eclipses with Spitzer–IRAC (Agol et al., 2010)> constraints on H<sub>2</sub>O and other molecules from Keck–NIRSPEC (Barnes et al., 2010)> inflation through Ohmic dissipation (Batygin & Stevenson, 2010)> line profile tomography probing star and planet rotations and orbit (Collier Cameron et al., 2010a)> atmospheric models and the effects of TiO, VO, CO, CH<sub>4</sub> (Fortney et al., 2010)> no evidence of star–planet magnetospheric interactions from CFHT polarimetry (Fares et al., 2010)> constraints on companions from transit time variations with NOT/WHT (Hrudková et al., 2010)> effect of night-side pollution on transit depth (Kipping & Tinetti, 2010)> high-temperature photochemistry and CH<sub>4</sub>, CO<sub>2</sub>, CO, and H<sub>2</sub>O abundances (Line et al., 2010)> evaporation rates (Lecavelier des Etangs, 2010)> observation with digital SLR cameras (Littlefield, 2010)> Ohmic dissipation (Perna et al., 2010b)> X-ray detection during transits probing coronal–magnetospheric structure from XMM–Newton (Pillitteri et al., 2010)> ground-based near-infrared emission spectrum from IRTF–SpeX (Swain et al., 2010a)> homogeneous analysis and light curve properties (Southworth, 2010)> stellar limb darkening from multicolour light curves (Abubekerov et al., 2011)> disentangling planetary signals from stellar activity (Boisse et al., 2011)> re-confirmation of polarised reflected light from multicolour observations (Berdyugina et al., 2011)> reflection effect (Budaj, 2011)> time-dependent magnetohydrodynamic simulation of interplanetary environment (Cohen et al., 2011a)> models of thermal phase variations for eccentric orbits (Cowan & Agol, 2011a)> directed follow-up approach for transit detection using low-cadence surveys (Dzigan & Zucker, 2011)> transit parameters at 3.6  $\mu\text{m}$  from Spitzer–IRAC (Désert et al., 2011d)> mass loss from extreme ultraviolet and X-ray radiation (Ehrenreich & Désert, 2011)> limits on molecular features from archival HST–NICMOS transmis-

sion spectroscopy (Gibson et al., 2011b)> mass-loss rates consistent with an atomic hydrogen/proton mixture (Guo, 2011)> alkali line absorption in Na I and K I (Jensen et al., 2011)> polarisation studies (Kostogryz et al., 2011)> radial velocity variations due to stellar activity from MOST/SOPHIE photometry (Lanza et al., 2011a)> limits on 150 MHz radio emission from GMRT (Lecavelier des Etangs et al., 2011)> determination of planet albedo from Subaru (Langford et al., 2011)> volatile enrichment and heavy elements (Mousis et al., 2011)> limits on 3.25  $\mu\text{m}$  line emission from Keck–NIRSPEC (Mandell et al., 2011)> disequilibrium C, O, and N chemistry, and enhanced abundances of CH<sub>4</sub>, NH<sub>3</sub>, and HCN (Moses et al., 2011)> X-ray activity when planet close to active stellar regions from XMM–Newton (Pillitteri et al., 2011)> equatorial superrotation (Showman & Polvani, 2011)> high-altitude haze from optical/near-ultraviolet transmission spectroscopy with HST–STIS (Sing et al., 2011b)> effects of CH<sub>4</sub> quenching (Visscher & Moses, 2011)> effects of stellar activity (Aigrain et al., 2012)> wavelength-dependent astrometric motion (Coughlin & López-Morales, 2012b)> secondary eclipse scanning from archival Spitzer–IRAC (de Wit et al., 2012)> modeling of archival HST–NICMOS transmission spectroscopy (Gibson et al., 2012b)> effect of tidal locking on magnetospheric and atmospheric evolution (Gibson et al., 2012a)> effect of clouds and hazes (Heng et al., 2012)> tidal effects and spin–orbit alignment from orbit eccentricity (Husnoo et al., 2012)> temperature–pressure profile and upper atmospheric heating from HST–STIS Na I doublet (Huitson et al., 2012)> limb darkening coefficients from 3d stellar atmosphere fits to HST data (Hayek et al., 2012)> H $\alpha$  in the transmission spectrum (Jensen et al., 2012)> non-equilibrium chemistry from 3.6 and 4.5  $\mu\text{m}$  Spitzer phase curves (Knutson et al., 2012)> variation in evaporation from Ly- $\alpha$  transmission spectroscopy with HST–STIS (Lecavelier des Etangs et al., 2012)> atmospheric structure and composition from secondary eclipse spectroscopy (Lee et al., 2012c)> secondary eclipse map and location of day-side hot spot from Spitzer–IRAC (Majewski et al., 2012)> ground-based near-infrared emission spectrum from IRTF–SpeX (Waldmann et al., 2012)> atmospheric escape in Ly- $\alpha$  from HST–STIS (Bourrier et al., 2013)> atmospheric chemistry (Venot et al., 2012)> neutral oxygen at 130 nm with HST–COS (Ben-Jaffel & Ballester, 2013)> 3d model of H escape (Bourrier & Lecavelier des Etangs, 2013)> H<sub>2</sub>O absorption in day-side atmosphere at 3.2  $\mu\text{m}$  from VLT–CRIRES (Birkby et al., 2013)> planet mass determination from atmospheric scale height (de Wit & Seager, 2013)> CO in day-side atmosphere at 2–2.3  $\mu\text{m}$  with VLT–CRIRES (de Kok et al., 2013)> 3d radiative-hydrodynamical simulations (Dobbs-Dixon & Agol, 2013)> albedo from HST–STIS at 290–570 nm imply deep blue planet colour (Evans et al., 2013)> host star spin-up by angular momentum transfer from planet (Guinan, 2013)> computation of albedo in terms of cloud properties (Heng & Demory, 2013)> variable transit curves predicted in ultraviolet due to stellar wind bow shocks (Llama et al., 2013)> atmospheric disequilibrium diagnostics (Line & Yung, 2013)> C/O modeling and confirmation of C-rich atmosphere (Moses et al., 2013c)> atmospheric heat redistribution efficiency drops as stellar insolation rises (Perez-Becker & Showman, 2013)> soft X-ray transit detection with Chandra–ACIS (Poppenhaeger et al., 2013)> effects of dust-dominated atmosphere on emission spectrum and phase curves (Pont et al., 2013)> 3d atmospheric circulation with magnetic drag and Ohmic dissipation (Rauscher & Menou, 2013)> atmospheric CO absorption from Keck–NIRSPEC (Rodler et al., 2013a)> Doppler signatures of atmospheric circulation (Showman et al., 2013a)> transmission spectrum from HST–NICMOS from blind-source separation (Waldmann et al., 2013)> chemical model (Agúndez et al., 2014a)> atmospheric clouds, and degeneracy between cloud properties and Na abundance (Barstow et al., 2014)> detecting exomoons via transiting plasma torus (Ben-Jaffel & Ballester, 2014)> evidence for H<sub>2</sub>O at 1.15 and 1.4  $\mu\text{m}$  from HST–WFC3 eclipses (Crouzet et al., 2014)> ground-based near-infrared transmission spectrum from IRTF–SpeX (Danielski et al., 2014)> analysis of rotating star spots using SOAP-2 (Dumusque et al., 2014a)> systematic atmospheric retrieval analysis (Line et al., 2014)> atmospheric composition of day–night terminators (Lee et al., 2014e)> orbit parameters versus atmospheric species (Miguel & Kaltenecker, 2014)> re-evaluation of Spitzer–IRAC primary transit observations (Morello et al., 2014)> H<sub>2</sub>O at 1.15 and 1.4  $\mu\text{m}$  from HST–WFC3 transits (McCullough et al., 2014a)> H<sub>2</sub>O abundance from HST–WFC3 transmission spectra (Madhusudhan et al., 2014b)> X-ray variability and high stellar activity due to angular momentum transfer from planet to star (Pillitteri et al., 2014a)>

- atmospheric circulation (Rauscher & Kempton, 2014)> assessment of CH<sub>4</sub> detection (Swain et al., 2014)> variability of spectral lines during transit (Shliakhetska et al., 2014)> re-analysis of secondary eclipse time series spectroscopy from Spitzer-IRS (Todorov et al., 2014)> magnetohydrodynamic simulations of upper atmosphere (Trammell et al., 2014)> location in Spitzer 3.6/4.5  $\mu\text{m}$  colour-magnitude diagram (Triaud, 2014)> equatorial waves and superrotation (Tsai et al., 2014)> atmospheric clouds, and relation between pressure, abundance, and particle size (Vahidinia et al., 2014)> favourable for polarisation studies (Wiktorowicz & Laughlin, 2014)> hot CH<sub>4</sub> using a comprehensive computed line list from ExoMol (Yurchenko et al., 2014)> first exoplanet transit observed with SOFIA (Angerhausen et al., 2015b)> compilation of light curves and transit timing (Baluev et al., 2015)> stellar diameter from CHARA (Boyajian et al., 2015)> analytical model of the Rossiter-McLaughlin effect (Baluev & Shaidulin, 2015)> centre-to-limb variations across the stellar Fraunhofer lines from transits (Czesla et al., 2015)> optical hydrogen absorption consistent with a thin bow shock leading the planet (Cauley et al., 2015)> chromatic Rossiter-McLaughlin effect (Di Gloria et al., 2015)> non-isothermal theory for interpreting Na lines in transmission spectra (Heng et al., 2015)> models of local and global cloud formation (Lee et al., 2015c)> spatially resolved eastward winds and planet rotation (Louden & Wheatley, 2015)> impact of stellar activity on X-ray and ultraviolet transits (Llama & Shkolnik, 2015)> gyrochronology and isochrone ages (Maxted et al., 2015b)> far ultraviolet variability of the host star and possible mass accretion from the planet (Pillitteri et al., 2015)> constraints on Bond albedo and day-night heat transport from secondary eclipse depths (Schwartz & Cowan, 2015)> time scales of radio emission variability (See et al., 2015)> search for reflected light (Valyavin et al., 2015a)> spectrally resolved detection of Na with HARPS (Wytenbach et al., 2015)> excess absorption in the emission cores of Ca II, H- $\alpha$ , and Na I D during transits (Barnes et al., 2016)> chromatic line-profile tomography (Borsa et al., 2016)> absence of polarisation from AAT-HIPPI (Bott et al., 2016)> rotation and winds from CO and H<sub>2</sub>O absorption from VLT-CRILES (Broggi et al., 2016)> variation in the pre-transit Balmer line signal (Cauley et al., 2016)> Rossiter-McLaughlin effect 'reloaded' (Cegla et al., 2016a)> extreme ultraviolet flux and the escaping atmosphere (Guo & Ben-Jaffel, 2016)> non-equilibrium cloud formation (Helling et al., 2016)> StarSim stellar activity modelling of the photometric and radial velocity curves (Herrero et al., 2016)> favourable for lightning-discharge studies during transit (Hodossán et al., 2016a)> atmospheric circulation (Kataria et al., 2016)> ultraviolet light curves attributed to outgassing from Trojan satellites on tadpole orbits (Kislyakova et al., 2016)> multiple-scattering polarised radiative transfer (Kopparla et al., 2016)> 3d radiative-hydrodynamic cloud modeling (Lee et al., 2016)> exosphere transit models compared with solar data from SDO (Llama & Shkolnik, 2016)> HST-WFC3 transmission spectra explained by solar composition atmospheres with patchy clouds (Line & Parmentier, 2016)> atmospheric escape of hot gas coupling plasma, photoionisation and Ly- $\alpha$  emission (Salz et al., 2016)> H<sub>2</sub>O in clear/cloudy atmospheres from infrared transit spectroscopy (Sing et al., 2016)> near ultraviolet transit depth attributed to planet atmosphere (Turner et al., 2016a)> envelope enrichment and predicted H<sub>2</sub>O abundance (Venturini et al., 2016)> spectral analysis based on temporal multifractality (Agarwal et al., 2017)> limits on H<sub>2</sub>O-vapour at 650 nm from HARPS (Allart et al., 2017)> atmospheric retrieval analysis with NEMESIS (Barstow et al., 2017)> effects of 3d thermal structure on 1d atmospheric retrieval (Blecic et al., 2017)> atmospheric Na from HARPS-N (Casasayas-Barris et al., 2017)> abnormal H $\alpha$  variability during near-transit observations (Cauley et al., 2017c)> seven H $\alpha$  transits using ESO-HARPS and Keck-HIRES from 2006-2015 (Cauley et al., 2017a)> unfeasibility of chromatic line-profile tomography (Cegla et al., 2017)> effect of stellar flares on upper atmosphere (Chadney et al., 2017)> theoretical phase curve assuming thermochemical equilibrium (Dobbs-Dixon & Cowan, 2017)> evolving magnetic field from Zeeman-Doppler imaging 2013-15 (Fares et al., 2017)> mode of the H $\alpha$  and Na transmission spectrum (Huang et al., 2017a)> atmospheric Na revealed by planet's orbital motion with VLT-UVES (Khalafinejad et al., 2017)> time-resolved VLT-UVES observations of a stellar flare during primary transit (Klocová et al., 2017)> atmospheric aerosols (Lavvas & Koskinen, 2017)> dynamical mineral clouds from atmospheric modeling (Lee et al., 2017)> atmospheric modeling with HELIOS (Malik et al., 2017)> models of transmitted and polarised scattered X-ray flux (Marin & Grosso, 2017)> Rossiter-McLaughlin effect determined from differential least-squares deconvolution (Strachan & Anglada-Escudé, 2017)> atmospheric modeling with reduced C-H-O chemical network, VULCAN (Tsai et al., 2017)> magnetospheric conditions and radio emission (Weber et al., 2017)> stellar absorption line centre-to-limb variations (Yan et al., 2017)> atmospheric structure and dynamics from Doppler-shifted emission spectra (Zhang et al., 2017a)>
- HD 209458** planet with  $P = 3.52$  d,  $M_p \sin i = 0.62 M_J$ ,  $R_p = 1.32 R_J$ ,  $a = 0.046$  au, transiting a  $1.1 M_{\odot}$  G0 dwarf at 47 pc, with  $\Delta F = 0.017$  mag; radial velocity discovery with Keck-HIRES (Henry et al., 2000)> transit detection (Henry et al., 1999)> (Henry et al., 2000)> (Charbonneau et al., 2000)> *a posteriori* detection in Hipparcos photometry: (Söderhjelm et al., 1999)> (Robichon & Arenou, 2000)> (Castellano et al., 2000)> limits on emission/absorption lines during transit (Bundy & Marcy, 2000)> multicolour transits (Jha et al., 2000)> spectroscopic orbit from Keck-HIRES (Mazeh et al., 2000)> first detection of Rossiter-McLaughlin effect with OHP-ELODIE (Queloz et al., 2000a)> transit photometry from HST-STIS (Brown et al., 2001)> prediction of molecular signatures during secondary eclipse (Brown, 2001b)> limb darkening (Deeg et al., 2001)> limits on emission/absorption lines during transit with VLT-UVES (Moutou et al., 2001)> Na concentration affected by non-LTE (Barman et al., 2002)> limits on CO at  $2.3 \mu\text{m}$  with Keck-NIRSPEC (Brown et al., 2002)> atmospheric Na at  $589.3$  nm with HST (Charbonneau et al., 2002)> star/planet parameters and stellar age of 5.2 Gyr (Cody & Sasselov, 2002)> transits with 0.25-m telescope (Hudgins & Filipović, 2002)> evolutionary models do not explain large planet radius by irradiation alone (Baraffe et al., 2003)> planet rotation from oblateness in transit photometry (Barnes & Fortney, 2003)> tidal and kinetic heating effects on planet radii (Bodenheimer et al., 2003)> age and irradiation may explain radius (Burrows et al., 2003a)> global circulation characterised by polar vortices and broad zonal jets (Cho et al., 2003)> atmospheric models of Na absorption (Fortney et al., 2003)> atmospheric H driven by H<sub>2</sub>O photolysis and reaction of OH with H<sub>2</sub> (Liang et al., 2003)> limits on He I at  $1083$  nm from VLT-ISAAC (Moutou et al., 2003)> limits on CH<sub>4</sub> from transmission spectroscopy at  $3.6 \mu\text{m}$  with VLT-ISAAC (Richardson et al., 2003b)> limits on CO and H<sub>2</sub>O absorption at  $2.2 \mu\text{m}$  from IRTF-SpeX (Richardson et al., 2003a)> extended/escaping upper atmosphere in Ly- $\alpha$  (Vidal-Madjar et al., 2003)> evaporation rate and lifetime versus planet mass (Baraffe et al., 2004)> effect of tidal locking on magnetospheric and atmospheric evolution (Grießmeier et al., 2004)> review (Ksanfomali, 2004)> atmospheric escape and atmospheric lifetime (Lecavelier des Etangs et al., 2004)> limits on Na absorption from comets with HET-HRS (Mendelowitz et al., 2004)> detection of O/C from HST-STIS (Vidal-Madjar et al., 2004)> limits on exospheric H $\alpha$  absorption from Subaru-HRS (Winn et al., 2004b)> atmospheric composition and global circulation at  $0.5$ - $25 \mu\text{m}$  from Spitzer-IRAC-MIPS (Burrows et al., 2005)> 3d atmospheric circulation models and predicted wind speeds (Cooper & Showman, 2005)> limits on CO at  $2 \mu\text{m}$  from Keck-NIRSPEC (Deming et al., 2005a)> atmospheric models of  $24 \mu\text{m}$  Spitzer data suggest re-radiation of stellar flux over entire planet (Fortney et al., 2005)> time-dependent radiative model and dependence of Na on orbit phase (Iro et al., 2005)> eccentricity from 85 radial velocity measurements during 1999-2005 from Keck/Lick (Laughlin et al., 2005b)> limits on atomic species from Subaru-HDS (Narita et al., 2005)> limits on secondary eclipse from ground-based K-band photometry with UKIRT (Snellen, 2005)> hydrodynamic escape of neutral gas (Tian et al., 2005)> obliquity tides as a persistent heat source for close-in orbits (Winn & Holman, 2005)> period accuracy  $0.016$  s from revised photometry/radial velocity (Wittenmyer et al., 2005)> limits on 150 MHz radio emission from GMRT (Winterhalter et al., 2005)> potential of integral field spectroscopy for Na I detection with WHT-INTEGRAL (Aribas et al., 2006)> disequilibrium abundances for CO and CH<sub>4</sub> (Cooper & Showman, 2006)> tests of general relativistic gravitoelectric correction require transit accuracies to  $0.1$  s (Iorio, 2006a)> dynamical constraints on quadrupole mass moment from orbital period (Iorio, 2006b)> albedo limit of  $0.25$  from MOST photometry (Rowe et al., 2006)> infrared radius from Spitzer-MIPS (Richardson et al., 2006)> discrepancy in transit colour (Tingley et al., 2006)> hot H absorption (Ballester et al., 2007)> H<sub>2</sub>O absorption (Barman, 2007)> theoretical spectral models with a thermal inversion and H<sub>2</sub>O emission (Burrows et al., 2007b)> absorption by atomic H with no indication of evaporation (Ben-Jaffel, 2007)> transit limits on companions from MOST (Croll et al., 2007a)> mid-infrared phase variations (Cowan et al.,

2007)> ground-based limits on secondary eclipse with IRTF (Deming et al., 2007b)> enhanced mass loss through hydrodynamic escape by stellar tidal forces (Erkaev et al., 2007)> modeling escape and composition of the irradiated atmosphere (García Muñoz, 2007)> limb darkening from HST-STIS (Knutson et al., 2007c)> dependence of evaporation rate on potential energy (Lecavelier des Etangs, 2007)> 3d hydrodynamical models and mass-loss rate (Schneider et al., 2007)> diagnostic potential of albedo measurements (Burrows et al., 2008b)> spectral, spatial, and temporal properties of H exosphere (Ben-Jaffel, 2008)> TiO and VO optical absorption from HST-STIS (Désert et al., 2008)> extended exosphere and hydrogen loss from HST-ACS (Ehrenreich et al., 2008)> energetic neutral atoms explains high-velocity hydrogen (Holmström et al., 2008)> lower albedos predicted by radiation transfer models (Hood et al., 2008)> atmospheric temperature inversion from 3.6–8.0  $\mu\text{m}$  emission spectrum with Spitzer-IRAC (Knutson et al., 2008)> Rayleigh scattering by H<sub>2</sub> and pressure–altitude relation (Lecavelier des Etangs et al., 2008c)> radiation pressure can account for high-velocity H atoms (Lecavelier des Etangs et al., 2008b)> limits on companion planets from transit time variations with MOST (Miller-Ricci et al., 2008b)> albedo limit of 0.04 from MOST (Rowe et al., 2008)> featureless emission spectrum over 7.4–15.2  $\mu\text{m}$  with Spitzer-IRS (Swain et al., 2008a)> atmospheric circulation with simplified forcing (Showman et al., 2008a)> ground-based detection of Na from Subaru-HDS (Snellen et al., 2008)> limb darkening from HST-STIS (Sing et al., 2008a)> temperature–pressure profile at terminator from Na absorption and Rayleigh scattering (Sing et al., 2008b)> homogeneous analysis and light curve properties: (Southworth, 2008)> reconfirmation of evaporation (Vidal-Madjar et al., 2008)> limb darkening mismatch with atmosphere models (Claret, 2009)> homogeneous analysis and light curve properties: (Southworth, 2009)> coupled radiative–dynamical atmospheric circulation (Showman et al., 2009)> H<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub> at 1.5–2.5  $\mu\text{m}$  from HST-NICMOS (Swain et al., 2009b)> light curve analysis (Abubekerov et al., 2010)> inflation through Ohmic dissipation (Batygin & Stevenson, 2010)> atmospheric H<sub>2</sub>O at 3.6–8.0  $\mu\text{m}$  with Spitzer-IRAC (Beaulieu et al., 2010b)> energetic atoms in upper atmosphere (Ben-Jaffel & Sona Hosseini, 2010)> photometric and spectral signatures of 3d models (Burrows et al., 2010)> radiative hydrodynamic simulations and temporal variability (Dobbs-Dixon et al., 2010)> magnetospheric properties from energetic neutral atoms (Ekenbäck et al., 2010)> atmospheric models and the effects of TiO, VO, CO, CH<sub>4</sub> (Fortney et al., 2010)> limits on far-ultraviolet aural/dayglow emission from HST-COS (France et al., 2010)> mass loss and tidal evolution (Guo, 2010)> relevance to testing (general relativistic like) Horava–Lifshitz gravity (Iorio & Ruggiero, 2010)> characterising the thermosphere with ultraviolet transit observations (Koskinen et al., 2010b)> evaporation rates (Lecavelier des Etangs, 2010)> tidal heating (Leconte et al., 2010a)> mass-loss from HST-COS consistent with models that include metals in outflowing gas (Linsky et al., 2010)> thermal inversion and molecular abundances (Madhusudhan & Seager, 2010)> limits on Trojan asteroids from MOST (Moldovan et al., 2010)> thermal inversion and molecular abundances (Madhusudhan & Seager, 2010)> effects of magnetic drag on atmospheric winds (Perna et al., 2010a)> Ohmic dissipation (Perna et al., 2010b)> suprathermal H produced by dissociation of molecular H<sub>2</sub> (Shematovich, 2010)> shifts in CO lines due to planet’s orbital velocity (Snellen et al., 2010a)> transits of limb-brightened lines and tentative Si IV absorption (Schlawin et al., 2010)> homogeneous analysis and light curve properties (Southworth, 2010)> directed follow-up approach for transit detection using low-cadence surveys (Dzigan & Zucker, 2011)> mass loss rate from extreme ultraviolet and X-ray radiation (Ehrenreich & Désert, 2011)> HST-COS observations and constraints (France et al., 2011)> mass-loss rates consistent with an atomic hydrogen/proton mixture (Guo, 2011)> coupled radius–orbit evolutionary models (Ibgui et al., 2011)> alkali line absorption in Na I and KI (Jensen et al., 2011)> spectroscopic methods for detecting scattered starlight (Langford et al., 2011)> limits on radio emission at 150 MHz from GMRT (Lecavelier des Etangs et al., 2011)> transmission spectroscopy accounting for eccentricity and longitude of pericentre (Montalto et al., 2011)> disequilibrium C, O, and N chemistry, and enhanced CH<sub>4</sub>, NH<sub>3</sub>, and HCN abundances (Moses et al., 2011)> temperature–pressure profile, ionisation layer, and thermosphere from Na D lines (Vidal-Madjar et al., 2011)> effects of atmospheric circulation (Agúndez et al., 2012)> wavelength-dependent astrometric motion (Coughlin & López-Morales, 2012b)> transit and eclipse parameters from Spitzer-MIPS 24  $\mu\text{m}$  observations (Crossfield et al., 2012c)> impact of circumplanetary jets on transit spectra and timing offsets (Dobbs-Dixon et al., 2012)> limb darkening coefficients from 3d stellar atmosphere fits to HST data (Hayek et al., 2012)> H $\alpha$  in the transmission spectrum (Jensen et al., 2012)> constraints on eccentricity from tidal dissipation (Laskar et al., 2012)> constraints on high-speed winds with atmospheric drag from anomalous Doppler shifts during transit (Miller-Ricci Kemp-ton & Rauscher, 2012)> atmospheric chemistry (Venot et al., 2012)> ground-based detection of Ca, and possibly Sc and H (Astudillo-Defru & Rojo, 2013)> 3d model of H escape with radiative blow-out and stellar wind interactions (Bourrier & Lecavelier des Etangs, 2013)> near-infrared transmission spectroscopy with HST-NICMOS (Deming et al., 2013)> photochemical–dynamical model for escaping heavy atoms (Koskinen et al., 2013a)> photochemical–dynamical model for escaping heavy atoms (Koskinen et al., 2013b)> 3d mixing and application to day–night cold trap (Parmentier et al., 2013)> atmospheric heat redistribution efficiency drops as stellar insolation rises (Perez-Becker & Showman, 2013)> 3d atmospheric circulation with magnetic drag and Ohmic dissipation (Rauscher & Menou, 2013)> Doppler signatures of atmospheric circulation (Showman et al., 2013a)> atomic Mg from HST-STIS, and confirmation of hydrodynamic escape (Vidal-Madjar et al., 2013)> chemical model (Agúndez et al., 2014a)> modeling Mg escape (Bourrier et al., 2014)> mass-loss rates (Cherenkov et al., 2014)> no evidence for atmospheric thermal inversion (Diamond-Lowe et al., 2014)> ionisation in thermosphere (Ionov et al., 2014)> thermal escape and mass-loss (Koskinen et al., 2014a)> effects of photoionisation on transit depth in K (Lavvas et al., 2014)> H<sub>2</sub>O abundance from HST-WFC3 transmission spectra (Madhusudhan et al., 2014b)> atmospheric circulation (Rauscher & Kempton, 2014)> magnetohydrodynamic atmosphere simulations (Rogers & Showman, 2014)> location in Spitzer 3.6/4.5  $\mu\text{m}$  colour–magnitude diagram (Triaud, 2014)> mass loss rates and stellar wind (Villarreal D’Angelo et al., 2014)> favourable for polarisation studies (Wiktowicz & Laughlin, 2014)> phase curve at 4.5  $\mu\text{m}$  from Spitzer-IRAC (Zellem et al., 2014b)> ground-based infrared emission spectra from IRTF-SpeX and Hale-TripleSpec (Zellem et al., 2014a)> no Si III from HST data in far ultraviolet (Ballester & Ben-Jaffel, 2015)> modeling Mg escape (Bourrier et al., 2015b)> stellar diameter from CHARA (Boyajian et al., 2015)> atmospheric heating by stellar radiation from soft X-rays to extreme ultraviolet (Ionov & Shematovich, 2015)> atmospheric mass loss including extreme ultraviolet irradiation and planetary magnetic dipole (Khodachenko et al., 2015)> gyrochronology and isochrone ages (Mxated et al., 2015b)> transmission spectroscopy using VLT-KMOS (Parviainen et al., 2015)> high-energy irradiation and mass-loss rates (Salz et al., 2015)> constraints on Bond albedo and day–night heat transport from secondary eclipse depths (Schwartz & Cowan, 2015)> evidence against strong thermal inversion from high-dispersion spectroscopy (Schwarz et al., 2015a)> magnetospheric models, bow shocks, and near-ultraviolet absorption (Alexander et al., 2016)> UK Meteorological Office global circulation model (Amundsen et al., 2016)> atmospheric parameters from HST spectrophotometry (del Burgo & Allende Prieto, 2016)> extreme ultraviolet flux and the escaping atmosphere (Guo & Ben-Jaffel, 2016)> non-equilibrium cloud formation (Helling et al., 2016)> atmospheric circulation (Kataria et al., 2016)> limits on H<sub>3</sub><sup>+</sup> from VLT-CRIRES (Lenz et al., 2016)> no thermal inversion and solar H<sub>2</sub>O abundance from HST-WFC3 (Line et al., 2016)> molecular formation throughout the region of atmospheric mass loss (Pinotti & Boechat-Roberty, 2016)> photoionisation of planetary winds (Schneider et al., 2016)> atmospheric escape of hot gas coupling plasma, photoionisation and Ly- $\alpha$  emission (Salz et al., 2016)> H<sub>2</sub>O in clear/cloudy atmospheres from infrared transit spectroscopy (Sing et al., 2016)> confirmation of H<sub>2</sub>O from HST-WFC3 with Bayesian spectral retrieval (Tsiaras et al., 2016b)> envelope enrichment and predicted H<sub>2</sub>O abundance (Venturini et al., 2016)> inferring inhomogeneous cloud cover from asymmetric transits (von Paris et al., 2016a)> atmospheric retrieval analysis with NEMESIS (Barstow et al., 2017)> C/O and O/H ratios suggest origin beyond the snow line (Brewer et al., 2017)> combining low- and high-resolution spectroscopy (Brogi et al., 2017)> effect of stellar flares on upper atmosphere (Chadney et al., 2017)> influence of coronal mass ejections on atmospheric mass-loss rate (Cherenkov et al., 2017)> Chandra-HRC observations confirm X-ray emission, ad derived mass-loss rates (Czesla et al., 2017)> photospheric spectral line profiles retrieved across the stellar disk (Dravins et al., 2017b)> atmospheric model accounting for stellar wind and planet’s intrinsic magnetic moment (Erkaev et al.,



2017)> models of Ly $\alpha$  absorption (Khodachenko et al., 2017)> inflated radius attributed to internal heating at depths of  $10^7$  Pa which suppresses planetary cooling (Komacek & Youdin, 2017)> atmospheric aerosols (Lavvas & Koskinen, 2017)> modeling the high-energy irradiation from HST-COS (ultraviolet) and XMM-Newton (Louden et al., 2017a)> evidence of N chemistry (NH $_3$ ) from HST-WFC3 (MacDonald & Madhusudhan, 2017b)> evidence of N chemistry (NH $_3$  and/or HCN), patchy clouds, and H $_2$ O (MacDonald & Madhusudhan, 2017a)> 3d atmospheric models of the deep atmosphere and zonal jets (Mayne et al., 2017)> inflated radius attributed to advection of potential temperature (Tremblin et al., 2017)> atmospheric modeling with reduced C-H-O chemical network, VULCAN (Tsai et al., 2017)> magnetospheric conditions and radio emission (Weber et al., 2017)> stellar absorption line centre-to-limb variations (Yan et al., 2017)> atmospheric structure and dynamics from Doppler-shifted emission spectra (Zhang et al., 2017a)> influence of stellar radiation pressure on planet envelope flow structure (Chererkov et al., 2018)>

**HD 219134** 6-planet low-mass system around bright ( $V = 5.5$ ) nearby ( $d = 6.5$  pc) star, all discovered from radial velocity measures (planets b and c also transit), with periods 3.1, 6.8, 22.8, 46.7, 94.2 and 2247 d; discovery of a 4-planet system from HARPS-N on La Palma-TNG (first of the HARPS-N Rocky Planet Search programme) with planet b transits discovered from Spitzer (Motalebi et al., 2015)> 2 additional planets, f and g, from Keck-HIRES and Lick-Levy (Vogt et al., 2015)> 12-yr stellar activity cycle from 27 yr of radial velocities (Johnson et al., 2016c)> planet c transits discovered from Spitzer (Gillon et al., 2017b)> Bayesian analysis of interior structure using stellar abundance proxies (Dorn et al., 2017a)> spatially-resolved spectroscopy across the stellar surface (Dravins et al., 2017b)>

## B. Discovered from transit photometry, ordered by identifier

### BD

**BD+20 594** see K2-56

### CoRoT

**CoRoT-1** discovery (Barge et al., 2008)> secondary eclipse in CoRoT data (Alonso et al., 2009a)> transit time analysis (Bean, 2009)> VLT transit and occultation photometry (Gillon et al., 2009b)> secondary eclipse from ARC (Rogers et al., 2009)> apsidal precession due to planetary tidal bulge (Ragozzine & Wolf, 2009)> low albedo (Snellen et al., 2009a)> transit time analysis (Csizmadia et al., 2010)> Rossiter-McLaughlin effect from Keck-HIRES and VLT-FORS (Pont et al., 2010)> pre-discovery transits from BEST (Rauer et al., 2010)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> secondary eclipse from Spitzer (Deming et al., 2011a)> photometry and new spectroscopy (Southworth, 2011)> prospects for detecting bow shocks (Vidotto et al., 2011a)> tidal effects on radial velocity (Arras et al., 2012)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> false-positive analysis (Nefs et al., 2012)> secondary eclipse from Palomar-WIRC (Zhao et al., 2012c)> confirmation of secondary eclipse (Parviainen et al., 2013)> atmospheric characterisation with HST-WFC3 (Ranjan et al., 2014)> constraints on TiO/VO from transmission spectrum with IRTF (Schlawin et al., 2014)> primary/secondary transit detections (Gibson, 2015)> no asymmetry in ground-based ultraviolet transits (Turner et al., 2016b)> heat recirculation and albedo from comparison of optical phase curve and secondary eclipse (von Paris et al., 2016b)> improved orbit and increased inflation from HARPS-N (Bonomo et al., 2017a)>

**CoRoT-2** highly active host star with optical variability caused by magnetic activity, highly inflated planet radius, and gravitationally bound stellar companion candidate, 2MASS J19270636+0122577; discovery (Alonso et al., 2008a)> Rossiter-McLaughlin effect (Bouchy et al., 2008)> secondary eclipse in CoRoT data (Alonso et al., 2009b)> star spot modeling and differential rotation (Fröhlich et al., 2009)> localisation of stellar activity (Huber et al., 2009)> star spot modeling and star-planet magnetic interaction (Lanza et al., 2009b)> star spot modeling and star-planet magnetic interaction (Pagano et al., 2009)> star spot eclipse mapping (Wolter et al., 2009)> secondary eclipse from WHT-LIRIS (Alonso et al., 2010)> host star chemistry

(Chavero et al., 2010)> thermal emission and tidal heating from Spitzer (Gillon et al., 2010c)> pre-discovery transits from BEST (Rauer et al., 2010)> star spot modeling (Silva-Valio et al., 2010)> atmospheric modeling from secondary eclipse (Snellen et al., 2010b)> secondary eclipse from Spitzer (Deming et al., 2011a)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> star spot and activity modeling (Guillot & Havel, 2011)> star-planet magnetic interactions (Lanza, 2011)> spot modeling and Rossiter-McLaughlin effect (Nutzman et al., 2011a)> spot modeling from 77 transits (Silva-Valio & Lanza, 2011)> stellar activity from VLT-UVES and Chandra (Schröter et al., 2011)> photometry and new spectroscopy (Southworth, 2011)> chromospheric Rossiter-McLaughlin effect (Czesla et al., 2012)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> C/O ratio as a characterisation of atmospheres (Madhusudhan, 2012)> physical properties (Southworth, 2012)> confirmed stellar companion from lucky imaging (Faedi et al., 2013b)> C/O modeling and confirmation of C-rich atmosphere (Moses et al., 2013c)> confirmation of secondary eclipse (Parviainen et al., 2013)> orbit parameters versus atmospheric species (Miguel & Kaltenecker, 2014)> black body spectrum from HST-WFC3 (Wilkins et al., 2014)> compilation of light curves and transit timing (Baluev et al., 2015)> gyrochronology and isochrone ages (Maxted et al., 2015b)> nearby star from lucky imaging (Wöllert et al., 2015)> disentangling planetary and stellar activity (Bruno et al., 2016)> orbital decay due to non-linear tidal dissipation (Essick & Weinberg, 2016)> improved orbit from HARPS-N (Bonomo et al., 2017a)> Spitzer photometry shows westward hotspot offset of 23° (Dang et al., 2018)>

**CoRoT-3** planet/brown dwarf (21M $_J$ ); discovery (Deleuil et al., 2008)> Rossiter-McLaughlin effect (Triaud et al., 2009)> host star chemistry (Chavero et al., 2010)> ellipsoidal modulation and relativistic beaming (Mazeh & Faigler, 2010)> limits on orbits and masses of moons (Weidner & Horne, 2010)> photometry and new spectroscopy (Southworth, 2011)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> stellar companion from lucky imaging (Faedi et al., 2013b)> secondary eclipse (Parviainen et al., 2013)> nearby star from lucky imaging (Wöllert et al., 2015)>

**CoRoT-4** discovery (Aigrain et al., 2008)> confirmation from radial velocity, and star and planet parameters (Moutou et al., 2008)> stellar rotation, differential rotation, and star-planet magnetic interaction (Lanza et al., 2009a)> host star (Chavero et al., 2010)> star-planet magnetic interactions (Lanza, 2011)> photometry and new spectroscopy (Southworth, 2011)> false-positive analysis (Nefs et al., 2012)> gyrochronology and isochrone ages (Maxted et al., 2015b)>

**CoRoT-5** discovery (Rauer et al., 2009)> host star (Chavero et al., 2010)> photometry and spectroscopy (Southworth, 2011)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)>

**CoRoT-6** discovery (Fridlund et al., 2010b)> photospheric activity, rotation, and star-planet magnetic interaction (Lanza et al., 2011b)> star-planet magnetic interactions (Lanza, 2011)> photometry and new spectroscopy (Southworth, 2011)> significant secondary eclipse (Parviainen et al., 2013)> gyrochronology and isochrone ages (Maxted et al., 2015b)>

**CoRoT-7** 2-planet system of which only planet b transits (planet c discovered by radial velocity); high stellar activity; discovery (Léger et al., 2009)> discovery of planet c from radial velocity (Queloz et al., 2009)> improved stellar parameters (Brunt et al., 2010)> possible planet d (Hatzes et al., 2010)> tidal evolution and atmospheric evaporation (Jackson et al., 2010)> photospheric activity and stellar rotation (Lanza et al., 2010)> evaporation rates (Lecavelier des Etangs, 2010)> interior composition (Rogers & Seager, 2010a)> composition and atmospheric evaporation (Valencia et al., 2010)> disentangling planetary signals from stellar activity (Boisse et al., 2011)> effects of magnetic drag and Ohmic dissipation (Castan & Menou, 2011)> mass determination (Ferraz-Mello et al., 2011)> tidal evolution (Greenberg & Van Laerhoven, 2011)> constraints on exosphere (Guenther et al., 2011)> mass determination (Hatzes et al., 2011)> atmospheric constraints, proposed lava ocean (Léger et al., 2011b)> thermal mass loss, and possible remnant of gas/ice giant (Leitzinger et al., 2011)> effects of stellar wind on exosphere and magnetosphere (Mura et al., 2011)> reassessment of radial velocity measurements (Pont et al., 2011a)> tidal decay and orbit circularisation (Rodríguez et al., 2011a)> photometry and new spectroscopy (Southworth, 2011)> prospects for detecting bow shocks (Vidotto et al., 2011a)> elliptical instability (Cebbron et al., 2012)> tidal evolution

- (Dong & Ji, 2012)> Spitzer observations and improved ephemeris (Fressin et al., 2012a)> composition modeling (Gong & Zhou, 2012)> atmospheric stability under tidal locking (Heng & Kopparla, 2012)> irradiation-driven mass-loss (Poppenhaeger et al., 2012a)> composition modeling and Fe-enrichment (Wagner et al., 2012)> stellar magnetic field topology (Fares et al., 2013)> mass loss by extreme ultraviolet and X-ray radiation (Kurokawa & Kaltenecker, 2013)> photophoretic separation of metals and silicates as an explanation for high density (Wurm et al., 2013)> new CoRoT transits and HARPS radial velocities (Barros et al., 2014a)> tidal evolution (Dong, 2014)> star spot modeling using CoRoT and HARPS data (Haywood et al., 2014b)> effects of stellar activity (Haywood et al., 2014a)> expected constraints on very hot super-Earths from JWST-NIRSPEC (Samuel et al., 2014)> gyrochronology and isochrone ages (Mxted et al., 2015b)> constraining planet structure from stellar chemistry (Santos et al., 2015a)> number of planetary signals present in radial velocity datasets (Faria et al., 2016a)> coupled orbital and spin evolution using a Maxwell viscoelastic rheology (Rodríguez et al., 2016)> constraint on super-Earth interiors from stellar abundances (Brugger et al., 2017)> Bayesian analysis of interior structure using stellar abundance proxies (Dorn et al., 2017a)> confirmation through 'Agatha' periodogram analysis (Feng et al., 2017a)> undetected giant planet predicted from formation model (Hoffmann et al., 2017)> cloud formation in metal-rich atmospheres (Mahapatra et al., 2017)>
- CoRoT-8** discovery (Bordé et al., 2010)> debris disks (Krivov et al., 2011)> photometry and new spectroscopy (Southworth, 2011)>
- CoRoT-9** longest period CoRoT planet ( $P = 95$  d); discovery (Deeg et al., 2010)> limits on orbits and masses of moons (Weidner & Horne, 2010)> transit time variations (Borkovits et al., 2011)> photometry and new spectroscopy (Southworth, 2011)> superrotating atmosphere in cyclostrophic balance (Peralta et al., 2014a)> 5 yr radial velocity suggest non-zero eccentricity (Bonomo et al., 2017b)> Spitzer constraints on rings and satellites (Lecavelier des Etangs et al., 2017)>
- CoRoT-10** discovery (Bonomo et al., 2010)> photometry and new spectroscopy (Southworth, 2011)>
- CoRoT-11** discovery and Rossiter-McLaughlin effect (Gandolfi et al., 2010)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> tidal analysis, candidate for orbit precession measurement (Lanza et al., 2011c)> photometry and new spectroscopy (Southworth, 2011)> line-profile tomography, Rossiter-McLaughlin effect (Gandolfi et al., 2012)>  $\text{CO} \rightleftharpoons \text{CH}_4$  time scales for orbital and vertical quenching for eccentric orbits (Visscher, 2012)> significant secondary eclipse (Parviainen et al., 2013)> nearby star from lucky imaging (Wöllert et al., 2015)>
- CoRoT-12** discovery (Gillon et al., 2010b)> photometry and new spectroscopy (Southworth, 2011)> new photometry and atmospheric models (Turner et al., 2017)>
- CoRoT-13** discovery (Cabrera et al., 2010)> photometry and new spectroscopy (Southworth, 2011)> marginally significant secondary eclipse (Parviainen et al., 2013)> gyrochronology and isochrone ages (Mxted et al., 2015b)>
- CoRoT-14** discovery (Tingley et al., 2011b)> photometry and new spectroscopy (Southworth, 2011)> tidal effects on radial velocity (Aras et al., 2012)>
- CoRoT-15** not in NASA; brown dwarf ( $63M_J$ ); discovery (Bouchy et al., 2011b)> photometry and new spectroscopy (Southworth, 2011)> significant secondary eclipse (Parviainen et al., 2013)>
- CoRoT-16** discovery (Ollivier et al., 2012)>
- CoRoT-17** discovery (Csizmadia et al., 2011)> photometry and new spectroscopy (Southworth, 2012)>
- CoRoT-18** discovery and Rossiter-McLaughlin effect (Hébrard et al., 2011b)> photometry and new spectroscopy (Southworth, 2012)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> marginally significant secondary eclipse (Parviainen et al., 2013)> gyrochronology and isochrone ages (Mxted et al., 2015b)>
- CoRoT-19** discovery and Rossiter-McLaughlin effect (Guenther et al., 2012)> photometry and new spectroscopy (Southworth, 2012)>
- CoRoT-20** high density ( $8.9\text{Mg m}^{-3}$ ), high eccentricity planet ( $e = 0.56$ ); discovery and tidal analysis (Delleuil et al., 2012)> photometry and new spectroscopy (Southworth, 2012)>
- CoRoT-21** not in NASA; extreme tidal forces leading to orbit decay and stellar spin-up in 800 Myr; discovery and tidal analysis,  $M_p = 2.3M_J$  (Pätzold et al., 2012)> secondary eclipse (Parviainen et al., 2013)>
- CoRoT-22** discovery (Moutou et al., 2014a)>
- CoRoT-23** discovery and tidal analysis (Rouan et al., 2012)> photometry and new spectroscopy (Southworth, 2012)> improved orbit from HARPS-N (Bonomo et al., 2017a)>
- CoRoT-24** 2-planet system, both transiting (first for CoRoT) with periods 5.1 d and 11.8 d; discovery (Alonso et al., 2014)> hydrodynamic escape rates and planetary radius (Lammer et al., 2016)> Roche lobe overflow model and mass-loss for short-period gaseous planets (Jackson et al., 2017b)>
- CoRoT-25** discovery (Almenara et al., 2013)>
- CoRoT-26** discovery (Almenara et al., 2013)>
- CoRoT-27** dense ( $12.6\text{Mg m}^{-3}$ )  $10M_J$  planet in a 3.6-d orbit; discovery (Parviainen et al., 2014)>
- CoRoT-28** slightly evolved star, G8/9IV (Cabrera et al., 2015)>
- CoRoT-29** possibly asymmetric transits, attributed to oblate star or spots; discovery (Cabrera et al., 2015)> chromatic light curves from GTC-OSIRIS do not confirm asymmetry (Pallé et al., 2016a)> transit profile and artificial megastructures (Wright et al., 2016b)>
- CoRoT-30...CoRoT-32** not in NASA
- CoRoT-33** not in NASA; brown dwarf ( $59M_J$ ) in the brown dwarf desert; discovery, 3:2 resonance with star rotation (Csizmadia et al., 2015)>
- CoRoT-ID 223977153** discovery (Bouffleur et al., 2018)>

## EPIC

(identifiers used as default alias in NASA Exoplanet Archive)

**EPIC-211822797** see K2-103**EPIC-220674823** see K2-106

## GJ

**GJ 1132** discovery by MEarth-South, and radial velocity confirmation by ESO-HARPS (Berta-Thompson et al., 2015)> predicted atmospheric composition (Schaefer et al., 2016)> simulations of radial velocity requirements to detect additional planets (Cloutier et al., 2017b)> constraints on additional bodies from transits/timings with MEarth-S and Spitzer (Dittmann et al., 2017a)> detection of atmospheric features suggesting  $\text{H}_2\text{O}$  and/or  $\text{CH}_4$  (Southworth et al., 2017)> suitability for JWST (Morley et al., 2017b)> application of scaling relations for rocky planet interiors (Zeng & Jacobsen, 2017)>

**GJ 1214** super-Earth at 15 pc, favourable for transmission spectroscopy; studies aim to establish whether the atmosphere is dominated by relatively heavy molecules such as  $\text{H}_2\text{O}$ , or high-altitude clouds obscuring its lower layers; discovery by MEarth (Charbonneau et al., 2009)> atmospheric constraints on composition (Bean et al., 2010a)> observable consequences of H-rich atmosphere (Miller-Ricci & Fortney, 2010)> composition modeling (Rogers & Seager, 2010b)> transit ephemeris (Sada et al., 2010)> atmospheric constraints from VLT/Magellan (Bean et al., 2011)> detectability of  $\text{CO}_2$  with HST (Belu et al., 2011)> stellar rotation (Berta et al., 2011)> atmospheric constraints from CFHT-WIRCam (Croll et al., 2011a)> atmospheric constraints from Keck-NIRSPEC (Crossfield et al., 2011)> transit times from Magellan (Carter et al., 2011c)> atmospheric constraints from Spitzer (Désert et al., 2011a)> transit search targeting known transiting systems (Gillon et al., 2011a)> transit times from APO (Kundurthy et al., 2011)> atmospheric constraints from Spitzer (Nettelmann et al., 2011)> atmospheric constraints from HST-WFC3 (Berta et al., 2012a)> atmospheric models (Benneke & Seager, 2012)> elliptical instability (Cebron et al., 2012)> wavelength-dependent astrometric motion (Coughlin & López-Morales, 2012b)> atmospheric constraints from INT/NOT/WHT (de Mooij et al., 2012)> tidal evolution (Dong & Ji, 2012)> atmospheric models (Howe & Burrows, 2012)> atmospheric stability under tidal locking (Heng & Kopparla, 2012)> atmospheric constraints from GTC-OSIRIS (Murgas et al., 2012)> atmospheric models (Menou, 2012a)> atmospheric models (Miller-Ricci Kempton et al., 2012)> star and planet properties (Anglada-Escudé et al., 2013b)> astrometric distance from CAPS, and infrared spectroscopy (Anglada-Escudé et al., 2013b)> extended cloudy  $\text{H}_2/\text{He}$  atmosphere (Barstow et al., 2013)> seven transits with UKIRT-WFC confirming featureless atmosphere (Colón & Gaidos, 2013)> transit depths in blue light, confirming limited atmosphere or small scale height dominated by  $\text{H}_2\text{O}$  (de Mooij et al., 2013a)> ultraviolet radiation environment (France et al., 2013)> Spitzer observations over 20 d, with atmospheric constraints from Rayleigh scat-

tering (Fraine et al., 2013)> population synthesis models of atmospheric composition (Fortney et al., 2013)> limits on transit time variations (Harpsoe et al., 2013)> 11 defocused transits, and limits on transit time variations (Harpsoe et al., 2013)> hydrodynamic blow-off of atmospheric H (Lammer et al., 2013b)> atmospheric models favour high clouds and hydrocarbon haze (Morley et al., 2013)> atmospheric constraints from IRSF-SIRIUS (Narita et al., 2013b)> Subaru photometry over 32 nights suggesting 1% H<sub>2</sub>O/99% N<sub>2</sub> atmosphere (Narita et al., 2013a)> atmospheric constraints from infrared transit photometry with ISF-SIRIUS (Narita et al., 2013b)> nine transits with Kuiper and STELLA-1 (Teske et al., 2013c)> atmospheric models suggesting H/He<7% by mass (Valencia et al., 2013)> simulations using the MIT general circulation model (Zalucha et al., 2013)> transit/eclipse from SOAR (Caceres et al., 2014)> tidal evolution (Dong, 2014)> limits on additional planet transits from Spitzer (Gillon et al., 2014b)> C<sub>2</sub>H<sub>2</sub> at 1.0–1.5 and 9–14 μm as a diagnostic for hydrocarbon-rich atmospheres (Hu & Seager, 2014)> atmospheric circulation (Kataria et al., 2014)> limits on cloud-free models dominated by H<sub>2</sub>O, CH<sub>4</sub>, CO, NO, or CO<sub>2</sub> from HST (Kreidberg et al., 2014b)> astrometry from CTIO-SMARTS (RECONS) and brown dwarf limits (Lurie et al., 2014)> X-ray coronal emission and evaporation rate from XMM-Newton (Lalitha et al., 2014)> atmospheric constraints from five GTC narrow-band transits (Wilson et al., 2014a)> atmospheric vertical mixing driven by anti-Hadley circulation (Charney et al., 2015a)> formation of high inhomogeneous atmospheric clouds (Charney et al., 2015b)> measures for characterising H<sub>2</sub>O-rich super-Earths (Madhusudhan & Redfield, 2015)> transmission spectroscopy using VLT-KMOS (Parviainen et al., 2015)> condensate clouds (KCl/ZnS, K<sub>2</sub>SO<sub>4</sub>/ZnO, graphite, etc) as functions of H/O and C/O (Mbarek & Kempton, 2016)> simultaneous optical and near-infrared photometry with SOFIA (Angerhausen et al., 2017)> unperturbed correlated noise removal for transit light curve fitting (Dehghan Firoozabadi et al., 2017)> optical transmission spectrum revealing heterogeneous stellar photosphere (Rackham et al., 2017)>

**GJ 9827** see K2–135

#### HAT

**HAT-P-1** discovery, and orbit around one component of a stellar binary (Bakos et al., 2007b)> 6 transits from ground photometry (Winn et al., 2007a)> Rossiter–McLaughlin effect (Johnson et al., 2008b)> radius (Liu et al., 2008a)> homogeneous analysis and light curve properties (Southworth, 2008)> six transits and refined parameters (Winn et al., 2008b)> light curve properties (Southworth, 2009)> light curve properties (Southworth, 2010)> secondary eclipse from Spitzer-IRAC (Todorov et al., 2010a)> secondary eclipse from WHT-LIRIS (de Mooij et al., 2011)> two secondary eclipses from HST-STIS (Béky et al., 2013)> near infrared transmission spectroscopy and 1.4 μm H<sub>2</sub>O band from HST-WFC3 (Wakeford et al., 2013)> stellar binary abundances (Liu et al., 2014a)> near infrared transmission spectroscopy, and Na/optical absorption from HST-STIS/WFC3 (Nikolov et al., 2014)> favourable for polarisation studies (Wiktorowicz & Laughlin, 2014)> constraints on optical transmission spectrum (Montalto et al., 2015b)> detection of K from GTC-OSIRIS (Wilson et al., 2015b)> cloudiness index based on transit radii associated with line centre/wing of Na/K (Heng, 2016)> atmospheric circulation (Kataria et al., 2016)> H<sub>2</sub>O in clear/cloudy atmospheres from infrared transit spectroscopy (Sing et al., 2016)> no asymmetry in ground-based ultraviolet transits (Turner et al., 2016b)> atmospheric retrieval analysis with NEMESIS (Barstow et al., 2017)>

**HAT-P-2** ≡ HD 147506; high eccentricity ( $e = 0.2$ ) hot Jupiter; discovery (Bakos et al., 2007a)> Rossiter–McLaughlin effect (Winn et al., 2007e)> Rossiter–McLaughlin effect (Loeillet et al., 2008b)> revised parameters from photometry and radial velocity (Pál et al., 2010)> homogeneous analysis and light curve properties (Southworth, 2010)> models of thermal phase variations for eccentric orbits (Cowan & Agol, 2011a)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> alkali line absorption in NaI and KI (Jensen et al., 2011)> Rossiter–McLaughlin effect (Albrecht et al., 2012b)> tidal effects on radial velocity (Arras et al., 2012)> CO $\rightleftharpoons$ CH<sub>4</sub> time scales for orbital and vertical quenching for eccentric orbits (Visscher, 2012)> stellar magnetic field topology (Fares et al., 2013)> orbit and secondary eclipse, day-side inversion, and trend in radial velocity from Spitzer (Lewis et al., 2013)> atmospheric circulation (Lewis et al., 2014)> atmospheric escape of hot gas coupling plasma, photoionisation and Ly- $\alpha$  emis-

sion (Salz et al., 2016)> formation by stellar perturbations (Shara et al., 2016)> improved orbit from HARPS-N (Bonomo et al., 2017a)> planet-induced stellar pulsations from 350 h of Spitzer 4.5 μm photometry (de Wit et al., 2017)> low-cost échelle spectroscopy (Garai et al., 2017)> marginally significant pre-discovery transits from Hipparcos (McDonald & Kerins, 2018)>

**HAT-P-3** discovery (Torres et al., 2007)> transit time analysis (Gibson et al., 2010b)> metal content from density (Chan et al., 2011)> transits from Asiago-TASTE (Nascimbeni et al., 2011a)> Rossiter–McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> transit photometry, size suggesting high metallicity (Chan et al., 2012)> photometry and new spectroscopy (Southworth, 2012)> transit and radial velocity fitting with EXOFAST (Eastman et al., 2013)> Spitzer-IRAC secondary eclipse photometry (Todorov et al., 2013)> new transit photometry (Ricci et al., 2017a)>

**HAT-P-4** discovery (Kovács et al., 2007)> search for additional planets from EPOXI (Ballard et al., 2011a)> 10 transits from EPOXI (Christiansen et al., 2011)> photometry and new spectroscopy (Southworth, 2011)> Rossiter–McLaughlin effect (Winn et al., 2011b)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> Spitzer-IRAC secondary eclipse photometry (Todorov et al., 2013)> signatures of rocky planet engulfment from metal enrichment and Li depletion (Saffe et al., 2017)>

**HAT-P-5** discovery (Bakos et al., 2007c)> debris disk (Krivov et al., 2011)> four-colour photometry (Southworth et al., 2012c)> new photometry and atmospheric models (Turner et al., 2017)>

**HAT-P-6** discovery (Noyes et al., 2008)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> Rossiter–McLaughlin effect and retrograde orbit (Hébrard et al., 2011a)> Rossiter–McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> internal gravity waves as explanation for apparent spin-orbit misalignment (Rogers et al., 2012)> photometry and new spectroscopy (Southworth, 2012)> atmospheric constraints from secondary eclipse with Spitzer-IRAC (Todorov et al., 2012)>

**HAT-P-7** ≡ Kepler-2; hot Jupiter in highly inclined (83°) orbit; discovery in pre-operational Kepler field (Pál et al., 2008)> 10-d photometry from Kepler commissioning (Borucki et al., 2009)> Rossiter–McLaughlin effect and retrograde orbit: Subaru-HDS (Narita et al., 2009b)> Rossiter–McLaughlin effect and retrograde orbit: Keck-HIRES (Winn et al., 2009d)> secondary eclipse from EPOXI, Spitzer, Kepler (Christiansen et al., 2010)> asteroseismology (Christensen-Dalsgaard et al., 2010)> thermal inversion and molecular abundances (Madhusudhan & Seager, 2010)> planetary structure in a tidally-relaxed inclined system (Mardling, 2010)> possible faint stellar companions (Narita et al., 2010b)> atmosphere and spectral models (Spiegel & Burrows, 2010)> ellipsoidal variations (Welsh et al., 2010)> search for additional planets from EPOXI (Ballard et al., 2011a)> photometry and new spectroscopy (Southworth, 2011)> prospects for detecting bow shocks (Vidotto et al., 2011a)> transits observed with Shandong/Weihai 1-m (Zhang et al., 2011)> Rossiter–McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> tidal effects on radial velocity (Arras et al., 2012)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> ellipsoidal variations (Jackson et al., 2012b)> reflected light from Kepler, mass from ellipsoidal variations (Mislis et al., 2012)> common proper motion companion and Kozai migration (Narita et al., 2012)> asteroseismology and revised planet parameters (Van Eylen et al., 2012)> internal gravity waves as explanation for apparent spin-orbit misalignment (Rogers et al., 2012)> light curve from 15 quarters of Kepler (Esteves et al., 2013)> confirmed stellar companion from lucky imaging (Faedi et al., 2013b)> 355 orbits from Kepler, cool spot due to planet-induced (stellar tidal) gravity darkening (Morris et al., 2013)> asteroseismology and revised planet parameters (Oshagh et al., 2013c)> atmospheric heat redistribution efficiency drops as stellar insolation rises (Perez-Becker & Showman, 2013)> 500 transits from Kepler, transit depth variations attributed to Kepler systematics (Van Eylen et al., 2013)> orbit polar rather than retrograde (Benomar et al., 2014)> stellar obliquity and seismology from Kepler (Lund et al., 2014)> constraints on oblateness (Zhu et al., 2014b)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> origin of high-order harmonics in Kepler light curves (Armstrong & Rein, 2015)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)> Kepler phase curves with beaming, ellipsoidal, and reflection phase modulation (Faigler & Mazeh, 2015)> spin-orbit angles from gravity darkening (Masuda,

- 2015)> nearby star from lucky imaging (Wöllert et al., 2015)> variation in phase curve peak offset attributed to variation in atmospheric wind speed (Armstrong et al., 2016a)> spin-orbit (retrograde) alignment from asteroseismology (Campante et al., 2016a)> use as a precision clock to constrain time variation of the gravitational constant (Masuda & Suto, 2016)> inferring inhomogeneous cloud cover from asymmetric transits (von Paris et al., 2016a)> heat recirculation and albedo from optical phase curve and secondary eclipse (von Paris et al., 2016b)> 3.6 and 4.5  $\mu\text{m}$  Spitzer phase curves (Wong et al., 2016)> simple transit model (Ji et al., 2017)> constraints on magnetic field strength (Rogers, 2017)>
- HAT-P-8** planet orbits primary of hierarchical triple system; discovery (Latham et al., 2009)> Rossiter-McLaughlin effect (Moutou et al., 2011a)> Rossiter-McLaughlin effect from OHP-SOPHIE (Simpson et al., 2011c)> atmospheric constraints from secondary eclipse with Spitzer (Todorov et al., 2012)> stellar companion from lucky imaging (Bergfors et al., 2013)> lucky imaging of host star (Faedi et al., 2013b)> low-mass binary companion from VLT-NACO (Ginski et al., 2013)> photometry with revised radius and mass (Mancini et al., 2013c)> Keck imaging indicates planet orbits primary of hierarchical triple system (Bechter et al., 2014)> three transits observed with Yunnan and Lijiang (Tan et al., 2014)> nearby star from lucky imaging (Wöllert et al., 2015)> simple transit model (Ji et al., 2017)>
- HAT-P-9** discovery (Shporer et al., 2009)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> Rossiter-McLaughlin effect (Moutou et al., 2011a)> revised ephemeris (Dittmann et al., 2012)> photometry and new spectroscopy (Southworth, 2012)>
- HAT-P-10** see WASP-11
- HAT-P-11**  $\equiv$  Kepler-3; discovery in pre-operational Kepler field (Bakos et al., 2010)> confirmation and revised ephemeris (Dittmann et al., 2009a)> interior composition (Rogers & Seager, 2010a)> Rossiter-McLaughlin effect and high-inclination orbit (Winn et al., 2010c)> models of thermal phase variations for eccentric orbits (Cowan & Agol, 2011a)> star spots over 26 Kepler transits (Deming et al., 2011b)> Rossiter-McLaughlin effect (Hirano et al., 2011b)> star spot analysis (Sanchis-Ojeda & Winn, 2011)> photometry and new spectroscopy (Southworth, 2011)> infrared transits and star spots (Sada et al., 2012)> possible GMRT 150 MHz radio emission (Lecavelier des Etangs et al., 2013)> analysis of rotating star spots using SOAP-T (Oshagh et al., 2013a)> spin-period ratio of 6:1 from Kepler star spots (Béky et al., 2014a)> semi-analytical model for spotted star transits, SPOTROD (Béky et al., 2014b)> detection of H<sub>2</sub>O in the transmission spectrum at 1.4  $\mu\text{m}$  (Fraine et al., 2014)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> prograde versus retrograde motion from star spot transit timing (Holczner et al., 2015)> gyrochronology and isochrone ages (Maxted et al., 2015b)> lightning as a possible source of planetary radio emission (Hodosán et al., 2016b)> HST-WFC3 transmission spectra explained by solar composition atmosphere with patchy clouds (Line & Parmentier, 2016)> use as a precision clock to constrain time variation of the gravitational constant (Masuda & Suto, 2016)> discovery of secondary eclipse from all short-cadence Kepler data (Huber et al., 2017)> star spot distribution suggests solar-like dynamo (Morris et al., 2017b)> chromospheric activity consistent with  $\geq 10$ -yr activity cycle (Morris et al., 2017a)>
- HAT-P-12** discovery (Hartman et al., 2009a)> ephemeris from 18 transits over 4.2 yr (Lee et al., 2012d)> possible transit duration variations from Pulkovo (Sokov et al., 2012)> transmission spectrum lacking H<sub>2</sub>O from HTS-WFC3 (Line et al., 2013a)> Spitzer-IRAC limits on secondary eclipse (Todorov et al., 2013)> broadband spectrophotometry from near ultraviolet to near infrared (Mallonn et al., 2015a)> atmospheric circulation (Kataria et al., 2016)> transits from Monterrey observatory (Sada & Ramón-Fox, 2016)> H<sub>2</sub>O in clear/cloudy atmospheres from infrared transit spectroscopy (Sing et al., 2016)> atmospheric retrieval analysis with NEMESIS (Barstow et al., 2017)> new photometry and atmospheric models (Turner et al., 2017)>
- HAT-P-13** 2-planet system; inner transiting  $e = 0.01$  hot Jupiter (planet b), and 15  $M_J$   $e = 0.67$  outer (non-transiting) planet c discovered from radial velocity; discovery (Bakos et al., 2009b)> predicted optical phase variations (Kane & Gelino, 2010)> planetary structure in a tidally-relaxed inclined system (Mardling, 2010)> absence of planet c transits (Szabó et al., 2010)> Rossiter-McLaughlin effect, possible planet d (Winn et al., 2010b)> 22 transits over 2.8 yr with one anomalous timing (Fulton et al., 2011)> transit times from Asiago-TASTE (Nascimbeni et al., 2011b)> variations in transit times (Pál et al., 2011)> transit time jitter (Payne & Ford, 2011)> constraints on metallicity and Love number (Kramm et al., 2012)> physical properties (Southworth et al., 2012a)> dynamical measures of internal structure from perturbations from a distant companion (Becker & Batygin, 2013)> secular orbit evolution and apsidal locking (Zhang et al., 2013a)> favourable for polarisation studies (Wiktorowicz & Laughlin, 2014)> dynamical constraints on core mass from eccentricity derived from Spitzer-IRAC transits (Buhler et al., 2016)> transits from Monterrey observatory (Sada & Ramón-Fox, 2016)> no asymmetry in ground-based ultraviolet transits (Turner et al., 2016b)> secondary eclipses and evidence for low core mass (Hardy et al., 2017)>
- HAT-P-14**  $\equiv$  WASP-27; near-grazing transit; discovery (Torres et al., 2010b)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> ephemeris (Nascimbeni et al., 2011a)> independent discovery as WASP-27 (Simpson et al., 2011a)> Rossiter-McLaughlin effect and retrograde orbit (Winn et al., 2011b)> photometry and new spectroscopy (Southworth, 2012)> simulated multi-colour photometry with MuSCAT (Fukui et al., 2016b)>
- HAT-P-15** discovery and composition (Kovács et al., 2010)>
- HAT-P-16** discovery (Buchhave et al., 2010)> Rossiter-McLaughlin effect from OHP-SOPHIE (Moutou et al., 2011a)> Rossiter-McLaughlin effect from Magellan/Keck (Albrecht et al., 2012b)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> simultaneous transit observations with two telescopes (Ciceri et al., 2013)> magnetic field constraints from near ultraviolet observations at Steward-Kuiper (Pearson et al., 2014b)> transits from Monterrey observatory (Sada & Ramón-Fox, 2016)>
- HAT-P-17** 2-planet system; inner transiting planet in short-period (10 d) eccentric ( $e = 0.34$ ) orbit, and outer (6000 d) non-transiting planet from radial velocity; discovery (Howard et al., 2012a)> Rossiter-McLaughlin effect from Keck-HIRES (Fulton et al., 2013)> favourable for polarisation studies (Wiktorowicz & Laughlin, 2014)> Kepler phase curves and secondary eclipses (Angerhausen et al., 2015a)> improved orbits from HARPS-N (Bonomo et al., 2017a)>
- HAT-P-18** discovery (Hartman et al., 2011b)> Rossiter-McLaughlin effect from HARPS-N (Esposito et al., 2014a)> ground-based transits (Seeliger et al., 2015)> Rayleigh scattering from WHT-ACAM transmission spectrum (Kirk et al., 2017)> photometric observations and transit solutions (Kjurkchieva et al., 2017b)>
- HAT-P-19** discovery and possible second planet (Hartman et al., 2011b)> Spitzer secondary eclipse observations at 3.6 and 4.5  $\mu\text{m}$  (Kammer et al., 2015)> transmission spectroscopy (Mallonn et al., 2015b)> ground-based transits (Seeliger et al., 2015)>
- HAT-P-20** discovery (Bakos et al., 2011a)> heavy-element composition of disk-instability planets (Boley et al., 2011)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> light curves, possible transit time variations (Granata et al., 2014)> favourable for polarisation studies (Wiktorowicz & Laughlin, 2014)> secondary eclipses from Spitzer (Deming et al., 2015)> Rossiter-McLaughlin effect from HARPS-N (Esposito et al., 2017)> system parameters and transit timings (Sun et al., 2017a)>
- HAT-P-21** short-period eccentric orbit with transits near apocentre; discovery (Bakos et al., 2011a)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> gyrochronology and isochrone ages (Maxted et al., 2015b)>
- HAT-P-22** discovery (Bakos et al., 2011a)> radial velocity search for massive long-period companion (Knutson et al., 2014c)> no asymmetry in ground-based ultraviolet transits (Turner et al., 2016b)> improved orbit from HARPS-N (Bonomo et al., 2017a)> 4.5  $\mu\text{m}$  secondary eclipse depths with Spitzer-IRAC (Kilpatrick et al., 2017)>
- HAT-P-23** discovery and short infall time (Bakos et al., 2011a)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> Rossiter-McLaughlin effect (Moutou et al., 2011a)> tidal effects on radial velocity (Arras et al., 2012)> four transits from UMO (Ramón-Fox & Sada, 2013)> near-infrared secondary eclipse from Spitzer/Palomar (O'Rourke et al., 2014)> physical properties from multicolour photometry (Ciceri et al., 2015b)> transits from Monterrey observatory (Sada & Ramón-Fox, 2016)> improved orbit from HARPS-N (Bonomo et al., 2017a)>
- HAT-P-24** discovery, prediction of large Rossiter-McLaughlin effect (Kipping et al., 2010)> predicted transit duration variations due to

- apsidal and nodal precession (Damiani & Lanza, 2011)> Rossiter-McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> parameters from Yunnan and Hokoon (Wang et al., 2013d)> observations with Rozhen 2-m telescope show no evidence for transit time or transit duration variations (Kjurkchieva et al., 2016)>
- HAT-P-25** discovery (Quinn et al., 2012a)>
- HAT-P-26** discovery (Hartman et al., 2011a)> limits on H<sub>2</sub>O from Magellan-LDSS-3C (Stevenson et al., 2016a)> prominent H<sub>2</sub>O-absorption from HST and Spitzer (Wakeford et al., 2017a)> preferred formation pathway through pebble accretion rather than planetesimal accretion (Ali-Dib & Lakhiani, 2018)>
- HAT-P-27** ≡ WASP-40; near-grazing transit; discovery (Béky et al., 2011)> independent discovery as WASP-40 (Anderson et al., 2011a)> Rossiter-McLaughlin effect (Brown et al., 2012b)> infrared transits (Sada et al., 2012)> ground-based transits (Seeliger et al., 2015)> nearby star from lucky imaging (Wöllert & Brandner, 2015)>
- HAT-P-28** discovery (Buchhave et al., 2011a)> nearby star from lucky imaging (Wöllert & Brandner, 2015)>
- HAT-P-29** discovery (Buchhave et al., 2011a)> radial velocity search for massive long-period companion (Knutson et al., 2014c)> nearby star from lucky imaging (Wöllert & Brandner, 2015)> improved orbit from HARPS-N (Bonomo et al., 2017a)>
- HAT-P-30** ≡ WASP-51; discovery and Rossiter-McLaughlin effect (Johnson et al., 2011c)> independent discovery as WASP-51 (Enoch et al., 2011a)> background stellar companions (Ginski et al., 2013)> transit observations (Maciejewski et al., 2016b)> favourable for polarisation studies (Wiktorowicz & Laughlin, 2014)> chromospheric activity, mass loss, and star-planet interaction (Staab et al., 2017)>
- HAT-P-31** discovery and possible second planet (Kipping et al., 2011)>
- HAT-P-32** discovery (Hartman et al., 2011c)> Rossiter-McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> primary transits and transmission spectra from Gemini-North MOS indicate clouds (Gibson et al., 2013b)> radial velocity search for long-period companion (Knutson et al., 2014c)> 45 transits from YETI and limbits on TTVs (Seeliger et al., 2014)> secondary eclipse photometry from Hale-WIRC/Spitzer-IRAC and stellar companion HAT-P-32B (Zhao et al., 2014)> transmission spectroscopy with LBT (Mallonn & Strassmeier, 2016)> transmission spectroscopy with GTC-OSIRIS (Nortmann et al., 2016)> broad band spectrophotometry (Mallonn et al., 2016)> stellar perturbations (Shara et al., 2016)> near-infrared transmission spectrum from HST-WFC3 (Damiano et al., 2017)> near ultraviolet transit photometry with LBT implies silicate aerosols (Mallonn & Wakeford, 2017)> thermal emission spectrum from HST-WFC3 (Nikolov et al., 2018)> high-precision (defocused) photometry of 8 transits with CAHA-BUSCA (Tregloan-Reed et al., 2018)>
- HAT-P-33** discovery (Hartman et al., 2011c)> new photometry and atmospheric models (Turner et al., 2017)> transit timing analysis from 8 transits with NAOC-Xinglong (Wang et al., 2017e)>
- HAT-P-34** high eccentricity and possible second planet; discovery (Bakos et al., 2012)> Rossiter-McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)>
- HAT-P-35** discovery (Bakos et al., 2012)> nearby star from lucky imaging (Wöllert & Brandner, 2015)>
- HAT-P-36** discovery (Bakos et al., 2012)> limits on transit time variations from 2009–2013 (Maciejewski et al., 2013c)> Rossiter-McLaughlin effect from HARPS-N (Mancini et al., 2015a)> orbital decay due to non-linear tidal dissipation (Essick & Weinberg, 2016)>
- HAT-P-37** discovery (Bakos et al., 2012)> additional transit observations (Maciejewski et al., 2016b)> new photometry and atmospheric models (Turner et al., 2017)>
- HAT-P-38** Saturn-like mass and radius; discovery (Sato et al., 2012a)> cloud modeling from HST-WFC3 (Bruno et al., 2018)>
- HAT-P-39** discovery (Hartman et al., 2012)>
- HAT-P-40** discovery (Hartman et al., 2012)>
- HAT-P-41** discovery (Hartman et al., 2012)> nearby star from lucky imaging (Wöllert et al., 2015)> Rossiter-McLaughlin effect (Johnson et al., 2017c)>
- HAT-P-42** discovery (Boisse et al., 2013)>
- HAT-P-43** discovery (Boisse et al., 2013)>
- HAT-P-44** 2-planet system, inner (planet b) transiting, outer non-transiting discovered from radial velocity (Hartman et al., 2014)>
- HAT-P-45** discovery (Hartman et al., 2014)>
- HAT-P-46** discovery (Hartman et al., 2014)>
- HAT-P-47** not in NASA; discovery (Bakos et al., 2016)
- HAT-P-48** not in NASA; discovery (Bakos et al., 2016)
- HAT-P-49** discovery and fast stellar rotation (Bieryla et al., 2014)>
- HAT-P-50** discovery (Hartman et al., 2015c)>
- HAT-P-51** discovery (Hartman et al., 2015c)>
- HAT-P-52** discovery (Hartman et al., 2015c)>
- HAT-P-53** discovery (Hartman et al., 2015c)>
- HAT-P-54** hot Jupiter in field 0 of K2 (Bakos et al., 2015a)>
- HAT-P-55** discovery (Juncher et al., 2015)>
- HAT-P-56** ≡ K2-20; inflated massive hot Jupiter followed up with K2 Campaign 0 (Huang et al., 2015a)> Rossiter-McLaughlin effect and super-synchronous spin-orbit alignment from Doppler tomography with TRES (Zhou et al., 2016b)> marginally significant pre-discovery transits from Hipparcos (McDonald & Kerins, 2018)>
- HAT-P-57** discovery and confirmation by Doppler tomography (Hartman et al., 2015a)>
- HAT-P-58...HAT-P-64** in preparation
- HAT-P-65** discovery (Hartman et al., 2016)>
- HAT-P-66** discovery (Hartman et al., 2016)>
- HAT-P-67** confirmation by Doppler tomography (Zhou et al., 2017a)>
- HATSouth**
- HATS-1** discovery (Penev et al., 2013)>
- HATS-2** discovery, star spots, and Rossiter-McLaughlin effect (Mohler-Fischer et al., 2013)> gyrochronology and isochrone ages (Maxted et al., 2015b)>
- HATS-3** discovery (Bayliss et al., 2013)> Rossiter-McLaughlin effect from AAT-UCLES (Addison et al., 2014)>
- HATS-4** discovery (Jordán et al., 2014)>
- HATS-5** discovery (Zhou et al., 2014a)>
- HATS-6** discovery (Hartman et al., 2015b)>
- HATS-7** not in NASA; discovery (Bakos et al., 2015b)>
- HATS-8** discovery (Bayliss et al., 2015)>
- HATS-9** in field 7 of K2; discovery (Brahm et al., 2015)> refined properties from K2 (Bayliss et al., 2018b)>
- HATS-10** in field 7 of K2; discovery (Brahm et al., 2015)>
- HATS-11** discovery (Rabus et al., 2016)> refined properties from K2 (Bayliss et al., 2018b)>
- HATS-12** discovery (Rabus et al., 2016)> refined properties from K2 (Bayliss et al., 2018b)>
- HATS-13** discovery (Mancini et al., 2015b)>
- HATS-14** discovery (Mancini et al., 2015b)> Rossiter-McLaughlin effect from Keck-HIRES (Zhou et al., 2015a)>
- HATS-15** discovery (Ciceri et al., 2016a)>
- HATS-16** discovery (Ciceri et al., 2016a)>
- HATS-17** discovery (Brahm et al., 2016b)>
- HATS-18** 2M<sub>J</sub> planet in 0.8 d orbit, with host star showing evidence of tidal spin-up; discovery (Penev et al., 2016)>
- HATS-19...HATS-21** not in NASA; discovery (Bhatti et al., 2017)
- HATS-22** discovery (Bento et al., 2017)>
- HATS-23** discovery (Bento et al., 2017)>
- HATS-24** discovery (Bento et al., 2017)>
- HATS-25** discovery (Espinoza et al., 2016a)>
- HATS-26** discovery (Espinoza et al., 2016a)>
- HATS-27** discovery (Espinoza et al., 2016a)>
- HATS-28** discovery (Espinoza et al., 2016a)>
- HATS-29** discovery (Espinoza et al., 2016a)>
- HATS-30** discovery (Espinoza et al., 2016a)>
- HATS-31** discovery (de Val-Borro et al., 2016)>
- HATS-32** discovery (de Val-Borro et al., 2016)>
- HATS-33** discovery (de Val-Borro et al., 2016)>
- HATS-34** discovery (de Val-Borro et al., 2016)>
- HATS-35** discovery (de Val-Borro et al., 2016)>
- HATS-36** discovery (Bayliss et al., 2018b)
- HATS-37...HATS-38** in preparation

**HATS-39** discovery (Bento et al., 2018)>  
**HATS-40** discovery (Bento et al., 2018)>  
**HATS-41** high-mass planet ( $9.7M_J$ ) orbiting highest metallicity transit host star ( $[Fe/H] = 0.47$ ); discovery (Bento et al., 2018)>  
**HATS-42** discovery (Bento et al., 2018)>  
**HATS-43 ... HATS-46** discovery (Brahm et al., 2018)  
**HATS-47 ... HATS-49** in preparation

In NASA Exoplanet Archive after 2018-01-01:

**HATS-50 ... HATS-53** discovery (Henning et al., 2018)

#### HD

(identifiers used as default alias in NASA Exoplanet Archive)

**HD 3167** see K2-96

**HD 106315** see K2-109

#### HIP

(identifiers used as default alias in NASA Exoplanet Archive)

**HIP 41378** see K2-93

**HIP 116454** see K2-2

#### KELT

**KELT-1** brown dwarf ( $27M_J$ ) orbiting  $V = 10.7$  F star; discovery and Rossiter-McLaughlin effect (Sivard et al., 2012)> secondary eclipse from Spitzer (Beatty et al., 2014)> compilation of light curves and transit timing (Baluev et al., 2015)> secondary eclipse with CFHT-WIRCam and limits on ground-based systematics (Croll et al., 2015a)> H-band emission spectrum at  $R = 50$  at 135 ppm from LBT-LUCI1 (Beatty et al., 2017a)>  
**KELT-2A** hot Jupiter transiting primary of HD 42176 binary; discovery, Kozai hypothesis and predicted Rossiter-McLaughlin effect (Beatty et al., 2012)>  
**KELT-3** discovery (Pepper et al., 2013)> search for  $H\alpha$  absorption (Cauley et al., 2017b)>  
**KELT-4A** hot Jupiter orbiting brightest component of hierarchical triple system (projected separation KELT-4A/4BC = 328 au, projected separation KELT-4B/4C = 10.30 au); discovery (Eastman et al., 2016)>  
**KELT-5** in preparation (Pepper, priv. comm.)  
**KELT-6** 2-planet system, outer non-transiting; detection, confirmation from radial velocity, and possibility of outer non-transiting planet (Collins et al., 2014)> Rossiter-McLaughlin effect for planet b and confirmation of planet c from HARPS-N (Damasso et al., 2015b)>  
**KELT-7** bright, rapidly rotating star; large Rossiter-McLaughlin effect (Bieryla et al., 2015)> super-synchronous spin-orbit alignment from Doppler tomography with TRES (Zhou et al., 2016b)>  
**KELT-8** low density inflated planet with large atmospheric scale height; discovery (Fulton et al., 2015a)>  
**KELT-9** hot planet ( $T_{eq} \sim 4600$  K) in 1.5-d orbit around an A/B star; discovery and Rossiter-McLaughlin effect (Gaudi et al., 2017)>  
**KELT-10** first KELT-South exoplanet; discovery (Kuhn et al., 2016)>  
**KELT-11** bright host star, highly inflated planet; discovery (Pepper et al., 2017b)> empirical stellar masses and radii from transits and (predicted) Gaia parallaxes (Beatty et al., 2017c)>  
**KELT-12** discovery (Stevens et al., 2017)>  
**KELT-13** see WASP-167  
**KELT-14**  $\equiv$  WASP-122; discovery (Rodriguez et al., 2016)> independent discovery as WASP-122 (Turner et al., 2016c)>  
**KELT-15** discovery (Rodriguez et al., 2016)>  
**KELT-16** planet near tidal disruption; discovery (Oberst et al., 2017)>  
**KELT-17** hot Jupiter in misaligned orbit; discovery and Rossiter-McLaughlin effect (Zhou et al., 2016c)>  
**KELT-18** discovery (McLeod et al., 2017)>  
**KELT-19A** hot Jupiter transiting Am star with distant stellar companion; discovery and Rossiter-McLaughlin effect (Sivard et al., 2018)>  
**KELT-20**  $\equiv$  MASCARA-2; hot Jupiter orbiting a  $V = 7.6$  mag A star; discovery (by KELT) and Rossiter-McLaughlin effect (Lund et al., 2017a)> independent discovery (by MASCARA) and Rossiter-McLaughlin effect (Talens et al., 2017b)>

In NASA Exoplanet Archive after 2018-01-01:

**KELT-21** discovery (Johnson et al., 2018)>

**KELT-22** discovery (Labadie-Bartz et al., 2018)>

#### Kepler

**Kepler-1** see TrES-2 (in pre-operational Kepler field)

**Kepler-2** see HAT-P-7 (in pre-operational Kepler field)

**Kepler-3** see HAT-P-11 (in pre-operational Kepler field)

**Kepler-4** discovery (Borucki et al., 2010b)> independent analysis, possible eccentric orbit, constraints on moons and Trojans (Kipping & Bakos, 2011a)> photometry and new spectroscopy (Southworth, 2011)> host star properties from Kepler asteroseismology (Huber et al., 2013b)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> secondary eclipse measurement of 7 ppm at phase 0.7 implying an eccentric orbit (Sheets & Deming, 2017)>

**Kepler-5** discovery (Koch et al., 2010b)> independent analysis, possible secondary eclipse, constraints on moons and Trojans (Kipping & Bakos, 2011a)> secondary eclipse from Spitzer (Désert et al., 2011c)> light curve modeling (Gostev, 2011)> photometry and new spectroscopy (Southworth, 2011)> secondary eclipses and phase variations (Esteves et al., 2013)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)> precision clock to constrain variation of the gravitational constant (Masuda & Suto, 2016)>

**Kepler-6** discovery (Dunham et al., 2010)> independent analysis, possible stellar rotation, constraints on moons and Trojans (Kipping & Bakos, 2011a)> secondary eclipse from Spitzer (Désert et al., 2011c)> light curve modeling (Gostev, 2011)> photometry and new spectroscopy (Southworth, 2011)> secondary eclipses and phase variations (Esteves et al., 2013)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)> precision clock to constrain variation of the gravitational constant (Masuda & Suto, 2016)>

**Kepler-7** discovery (Latham et al., 2010)> secondary eclipse, high albedo, and atmospheric modeling (Demory et al., 2011b)> light curve modeling (Gostev, 2011)> secondary eclipse, constraints on moons and Trojans (Kipping & Bakos, 2011a)> photometry and new spectroscopy (Southworth, 2011)> physical properties (Southworth, 2012)> atmospheric modeling (Demory et al., 2013a)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)> model of visible-wavelength phase curves (Hu et al., 2015a)> clouds maps derived from phase curve (Garcia Munoz & Isaak, 2015)> atmospheric modeling, with westward phase shift of brightest region explained by clouds (Shporer & Hu, 2015)> use as a precision clock to constrain time variation of the gravitational constant (Masuda & Suto, 2016)> interpretation of phase curves using scattering within the FMS general circulation model (Oreshenko et al., 2016)> inferring inhomogeneous cloud cover from asymmetric transits (von Paris et al., 2016a)> inhomogeneous aerosols and atmospheric circulation (Roman & Rauscher, 2017)>

**Kepler-8** discovery and Rossiter-McLaughlin effect (Jenkins et al., 2010a)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> constraints on moons and Trojans (Kipping & Bakos, 2011a)> photometry and new spectroscopy (Southworth, 2011)> Rossiter-McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> secondary eclipses and phase variations (Esteves et al., 2013)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)>

**Kepler-9** 3-planet system, outer two close to 2:1 commensurability; discovery by transit time variations (Holman et al., 2010)> composition modeling and Fe-enrichment (Havel et al., 2011)> light curve modeling and confirmation of planet d (Torres et al., 2011)> composition (Gong & Zhou, 2012)> orbit from transit times and radial velocities from TRADES (Borsato et al., 2014)> Rossiter-McLaughlin effect for the multi-planet system is consistent with spin-orbit alignment (Wang et al., 2018a)> ground-based photometry, dynamical modeling, and recovery of transit ephemeris (Wang et al., 2018b)>

**Kepler-10** 2-planet system including first (small) Kepler rocky planet; discovery and asteroseismology (Batalha et al., 2011)> effects of magnetic drag and Ohmic dissipation (Castan & Menou, 2011)> confirmation of planet c (Fressin et al., 2011)> mass loss constrains origin

- of rocky nature (Leitzinger et al., 2011)> lava ocean and prediction of secondary eclipse (Rouan et al., 2011)> additional planets predicted from packed planetary systems hypothesis (Fang & Margot, 2012b)> composition and Fe-enrichment (Gong & Zhou, 2012)> capture into spin-orbit resonance (Rodríguez et al., 2012)> composition and Fe-enrichment (Wagner et al., 2012)> tidal evolution (Dong & Ji, 2013)> atmospheric mass loss (Kurokawa & Kaltenegger, 2013)> photophoretic separation of metals and silicates as an explanation for high density (Wurm et al., 2013)> mass determination from HARPS-N (Dumusque et al., 2014b)> tidal evolution (Dong, 2014)> stellar parameters from asteroseismology (Fogtman-Schulz et al., 2014)> synchronisation and circularisation through tidal heating (Makarov & Efroimsky, 2014)> secondary eclipse (Sheets & Deming, 2014)> N-body constraints on collision and merger history (Terquem, 2014)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015a)> model of visible-wavelength phase curves (Hu et al., 2015a)> planet structure and Fe content (Santos et al., 2015a)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)> stellar chemical composition compared with 14 stellar twins (Liu et al., 2016b)> planet masses and densities (Weiss et al., 2016)> constraint on super-Earth interiors from stellar abundances (Brugger et al., 2017)> interior structure from stellar abundance proxies (Dorn et al., 2017a)> resolution of (HARPS-N and Keck-HIRES) mass discrepancy and improved mass for planet c (Rajpaul et al., 2017)>
- Kepler-11** 6-planet system, five tightly packed; discovery, coplanarity and stability (Lissauer et al., 2011a)> *in situ* accretion versus atmospheric erosion (Ikoma & Hori, 2012)> mass loss and system evolution (Lopez et al., 2012)> N-body modeling and stability (Migaszewski et al., 2012)> low densities for all six planets from mass-radius combinations (Lissauer et al., 2013)> hydrodynamic blow-off of atmospheric H (Lammer et al., 2013b)> H coronae around a CO<sub>2</sub>-dominated planetary atmosphere (Bernard et al., 2014)> accretion and evolution models (Bodenheimer & Lissauer, 2014)> orbit from transit times and radial velocities from TRADES (Borsato et al., 2014)> phase modulation of collective planetary system (Gelino & Kane, 2014)> formation of tightly packed systems (Hands et al., 2014)> stellar wind interaction and thermal escape (Kislyakova et al., 2014)> system stability, and close proximity to disruptive two-body mean-motion resonances (Mahajan & Wu, 2014)> superrotating atmosphere in cyclostrophic balance (Peralta et al., 2014a)> formation beyond the snow line, followed by inward migration, circularisation, and mass loss (Howe & Burrows, 2015)> *in situ* and *ex situ* formation models (D'Angelo & Bodenheimer, 2016)> extreme ultraviolet flux and the escaping atmosphere (Guo & Ben-Jaffel, 2016)> orbital dynamics and mean motion resonances (Mia & Kushvah, 2016)> young main sequence solar twin (Bedell et al., 2017)> dynamical studies focusing on grazing collisions, scatterings and mergers (Hwang et al., 2017)> constraints on outer planet architecture from co-planarity (Jontof-Hutter et al., 2017)>
- Kepler-12** low-density highly-inflated planet; discovery and atmospheric characterisation (Fortney et al., 2011a)> photometry and new spectroscopy (Southworth, 2012)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)> atmospheric modeling, with westward phase shift of brightest region and substellar point explained by clouds (Shporer & Hu, 2015)> use as a precision clock to constrain time variation of the gravitational constant (Masuda & Suto, 2016)>
- Kepler-13** KOI-13 in NASA (Kepler-13A); short-period (1.7-d) planet orbiting brighter component of hierarchical triple stellar system; out-of-eclipse light curve has comparable contributions from planet and ellipsoidal variations induced in the star; candidate identification (Borucki et al., 2011b)> spin-orbit alignment from gravity-darkened host star rotation (Barnes et al., 2011b)> speckle imaging (Howell et al., 2011)> confirmation from orbit modeling of variability and tidal distortions: (Shporer et al., 2011)> orbit modeling (Szabó et al., 2011)> orbit modeling (Mazeh et al., 2012)> orbit modeling (Mislis & Hodgkin, 2012)> spin-orbit resonance, transit duration variations, and precession of orbit plane (Szabó et al., 2012)> third stellar component (Santerne et al., 2012b)> secondary eclipses and phase variations, including third harmonic (Esteves et al., 2013)> misaligned prograde orbit from Rossiter-McLaughlin effect/Doppler tomography with HET (Johnson et al., 2014b)> reflection, beaming, and ellipsoidal variations from EXONEST (Placek et al., 2014)> atmospheric characterisation and day-side temperature (Shporer et al., 2014)> transit duration, peak depth and asymmetry changes due to rapid orbit precession (Szabó et al., 2014)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> origin of high-order harmonics in Kepler light curves (Armstrong & Rein, 2015)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)> Kepler phase curves with beaming, ellipsoidal, and reflection phase modulation (Faigler & Mazeh, 2015)> spin-orbit angles from gravity darkening (Masuda, 2015)> use as a precision clock to constrain time variation of the gravitational constant (Masuda & Suto, 2016)> atmospheric cold-trap processes in the non-inverted emission spectrum from HST-WFC3 (Beatty et al., 2017b)> spin-orbit angles from gravity darkening (Howarth & Morello, 2017)> stellar and planet parameters from Hawaii parallax programme (Mann et al., 2017a)> Rossiter-McLaughlin effect (Herman et al., 2018)>
- Kepler-14** planet orbiting one component of binary system; discovery (Buchhave et al., 2011b)> photometry and new spectroscopy (Southworth, 2012)> host star properties from Kepler asteroseismology (Huber et al., 2013b)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)>
- Kepler-15** discovery and composition modeling (Endl et al., 2011)> photometry and new spectroscopy (Southworth, 2012)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)>
- Kepler-16(AB)** circumbinary planet, comprising Saturn-mass giant in coplanar circular orbit ( $P = 229$  d) around eccentric binary ( $P = 41$  d); the planet will cease transiting the secondary in 2014, and the primary in 2018, thereafter non-transiting until 2042; discovery (Doyle et al., 2011)> Rossiter-McLaughlin effect indicating co-alignment of stellar orbit, planet orbit, and primary rotation (Winn et al., 2011a)> dynamical mass ratio of stellar components (Bender et al., 2012)> regions of dynamical stability for disks and planets (Jaime et al., 2012)> N-body planetesimal accretion (Meschiari, 2012a)> N-body planetesimal accretion (Marzari et al., 2012)> difficulties with *in situ* formation (Paardekooper et al., 2012)> habitable zone (Quarles et al., 2012b)> formation via gravitational instability (Zhu et al., 2012a)> analytic method for predicting eclipse timing variations (Armstrong et al., 2013)> eccentricity damped by circumbinary disk (Dunhill & Alexander, 2013)> determination of habitable zone (Kane & Hinkel, 2013)> determination of habitable zone (Liu et al., 2013b)> analytic theory for binary orbits (Leung & Lee, 2013)> influence of circumbinary disk gravity on planetesimal accumulation (Marzari et al., 2013)> rotational synchronisation and the habitable zone (Mason et al., 2013)> migration and gas accretion (Pierens & Nelson, 2013)> dynamical stability of 11:2 resonance bounded by unstable 5:1 and 6:1 resonances (Popova & Shevchenko, 2013)> climate modeling of habitable zone (Forgan, 2014)> multi-orbital 'tight transits' (Liu et al., 2014b)> circumbinary planet formation in debris belt (Meschiari, 2014)> dynamical stability (Chavez et al., 2015)> surface flux illumination and photosynthesis in circumbinary systems (Forgan et al., 2015)> analytic orbit propagation for circumbinary planets (Georgakarakos & Eggli, 2015)> circumbinary modeling in protoplanetary disks (Lines et al., 2015)> habitability zones versus radiation and plasma environment (Zuluaga et al., 2016)> role of disk self-gravity in orbital evolution (Mutter et al., 2017a)>
- Kepler-17** discovery, obliquity from star spots, secondary eclipse, and atmospheric characterisation (Désert et al., 2011b)> evidence for companion planets from transit timing variations (Steffen et al., 2010)> independent confirmation from radial velocity (Bonomo et al., 2012b)> star spots and stellar rotation (Bonomo & Lanza, 2012)> photometry and new spectroscopy (Southworth, 2012)> differential stellar rotation (Reinhold et al., 2013)> spin-orbit ratio not exactly 8:1 (Béky et al., 2014a)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> prograde versus retrograde motion from star spot transit timing (Holczer et al., 2015)> gyrochronology and isochrone ages (Maxted et al., 2015b)> stellar magnetic cycles (Estrela & Valio, 2016)> use as a precision clock to constrain time variation of the gravitational constant (Masuda & Suto, 2016)> stellar activity and rotation (Valio et al., 2017)>
- Kepler-18** 3-planet system, outer two (c and d) near 2:1 mean motion resonance; discovery through transit time variations, radial velocity variations, and Spitzer observations (Cochran et al., 2011)> masses from correlated transit time variations near mean motion resonance (Montet & Johnson, 2013)>
- Kepler-19** 3-planet system; planet d (non-transiting) from radial velocity; discovery of planet b, prediction of (non-transiting) planet c from transit time variations (Ballard et al., 2011b)> small planets have low eccentricities (Van Eylen & Albrecht, 2015)> confirmation of planet c

- and discovery of planet d (non-transiting) from radial velocity (Maltova et al., 2017)>
- Kepler-20** 6-planet system, 3 sub-Neptune and 2 of Earth mass which are transiting; planet g (non-transiting) from radial velocity; three massive planets b, c, d and two low-mass candidates (Gautier et al., 2012)> confirmation of the  $1.0R_{\oplus}$  and  $0.9R_{\oplus}$  planets e and f (Fressin et al., 2012b)> analysis of phase variations over the orbit (Kane & Gelino, 2013)> mapping of the interstellar medium (Johnson et al., 2015b)> discovery of non-transiting planet g from radial velocity (Buchhave et al., 2016)> effect of unseen additional perturber (Becker & Adams, 2017)> application of scaling relations for rocky planet interiors (Zeng & Jacobsen, 2017)>
- Kepler-21** discovery and asteroseismology (Howell et al., 2012)> confirmation as single star from CHARA-PAVO (Huber et al., 2012b)> asteroseismology (Valliappan & Karoff, 2012)> stellar companion from lucky imaging (Ginski et al., 2016a)> radial velocity measurements from TNG (López-Morales et al., 2016)>
- Kepler-22** first Kepler habitable zone planet; discovery and location within habitable zone (Borucki et al., 2012)> habitable zone (Neubauer et al., 2012)> search for exomoons (Heller & Barnes, 2013)> search for exomoons (Kipping et al., 2013a)> host star properties of Kepler's habitable planets (Armstrong et al., 2016b)>
- Kepler-23** 3-planet system; confirmation of planets b and c from correlated transit time variations and dynamical stability (Ford et al., 2012a)> host star properties from Kepler asteroseismology (Huber et al., 2013b)> planet d from Kepler (Rowe et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-24** 4-planet system; confirmation of planets b and c from transit time variations and dynamical stability (Ford et al., 2012a)> planets c and d from Kepler (Rowe et al., 2014)>
- Kepler-25** 3-planet system, planets b and c from transits, planet d from radial velocity; confirmation of planets b and c from correlated transit time variations and dynamical stability (Steffen et al., 2012a)> low stellar obliquity from Rossiter-McLaughlin effect (Albrecht et al., 2013)> host star properties from Kepler asteroseismology (Huber et al., 2013b)> 3d spin-orbit angle from asteroseismology, light curve, and Rossiter-McLaughlin effect (Benomar et al., 2014)> planet d, and improved masses, sizes, and orbits (Marcy et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)> spin-orbit alignment from asteroseismology (Campante et al., 2016a)>
- Kepler-26** 4-planet system; confirmation of planets b and c from correlated transit time variations and dynamical stability (Steffen et al., 2012a)> d and e from further light curve analysis (Rowe et al., 2014)> gravitational quantisation of orbits (Geroyannis, 2015)> dynamical masses from transit time variations (Jontof-Hutter et al., 2016)> reversibility applied to orbital dynamics (Panichi et al., 2017b)>
- Kepler-27** 2-planet system; confirmation from transit time variations and dynamical stability (Steffen et al., 2012a)>
- Kepler-28** 2-planet system; confirmation from transit time variations and dynamical stability (Steffen et al., 2012a)>
- Kepler-29** 2-planet system, likely in a 9:7 mean motion resonance; confirmation from transit time variations and dynamical stability (Fabrycky et al., 2012)> dynamical masses from transit time variations (Jontof-Hutter et al., 2016)> origin and dynamics of the 9:7 mean motion resonance (Migaszewski et al., 2017)> migration-induced formation of the 9:7 resonance (Migaszewski, 2017)> reversibility error method applied to orbital dynamics (Panichi et al., 2017b)>
- Kepler-30** 3-planet system with TTVs exceeding 2 d; transit time variations and dynamical stability (Fabrycky et al., 2012)> transits over star spot indicates orbits aligned with stellar equator (Sanchis-Ojeda et al., 2012)> mass-radius relation (Batygin & Stevenson, 2013)> transits over star spot (Sanchis-Ojeda et al., 2013b)> gyrochronology and isochrone ages (Maxted et al., 2015b)> orbit architecture, formation, long-term evolution (Panichi et al., 2017a)>
- Kepler-31** 3-planet system; confirmation of planets b and c from correlated transit time variations and dynamical stability (Fabrycky et al., 2012)> planet d from light curve analysis (Rowe et al., 2014)>
- Kepler-32** 5-planet system; planets b and c from transit time variations and dynamical stability (Fabrycky et al., 2012)> discovery of planets d, e, f, and evidence that planets formed at larger orbital radii and migrated inward (Swift et al., 2013)> stellar activity from Kepler (Savanov & Dmitrienko, 2013)> formation of tightly packed systems (Hands et al., 2014)> host star photometric variability and rotation from Kepler (Savanov & Dmitrienko, 2015b)>
- Kepler-33** closely-packed 5-planet system; confirmation from statistics of multiple transits (Lissauer et al., 2012b)> analysis of phase variations over the orbit (Kane & Gelino, 2013)> Titius-Bode type relation (Migaszewski et al., 2013)>
- Kepler-34(AB)** circumbinary planet; discovery (Welsh et al., 2012)> difficulties with *in situ* formation (Paardekooper et al., 2012)> analytic method for predicting eclipse timing variations (Armstrong et al., 2013)> habitable zone (Kane & Hinkel, 2013)> habitable zone (Liu et al., 2013b)> analytic theory for binary orbits (Leung & Lee, 2013)> rotational synchronisation and the habitable zone (Mason et al., 2013)> migration and gas accretion (Pierens & Nelson, 2013)> climate modeling of habitable zone (Forgan, 2014)> multi-orbital 'tight transits' (Liu et al., 2014b)> formation models including planetesimal self-gravity exclude *in situ* formation (Lines et al., 2014)> dynamical stability (Chavez et al., 2015)> analytic orbit propagation for circumbinary planets (Georgakarakos & Eggl, 2015)> evolution of circumbinary planets around eccentric binaries (Kley & Haghighipour, 2015)> circumbinary modeling in protoplanetary disks (Lines et al., 2015)> survival through post-common-envelope stage (Kostov et al., 2016a)> scattering of circumbinary planets to explain orbit configuration (Gong & Ji, 2017)> role of disk self-gravity in orbit evolution (Mutter et al., 2017a)> climate models (Wang & Cuntz, 2017)>
- Kepler-35(AB)** circumbinary planet; discovery (Welsh et al., 2012)> difficulties with *in situ* formation (Paardekooper et al., 2012)> analytic method for predicting eclipse timing variations (Armstrong et al., 2013)> habitable zone (Kane & Hinkel, 2013)> habitable zone (Liu et al., 2013b)> analytic theory for binary orbits (Leung & Lee, 2013)> rotational synchronisation and the habitable zone (Mason et al., 2013)> migration and gas accretion (Pierens & Nelson, 2013)> climate modeling of habitable zone (Forgan, 2014)> multi-orbital 'tight transits' (Liu et al., 2014b)> dynamical stability (Chavez et al., 2015)> analytic orbit propagation for circumbinary planets (Georgakarakos & Eggl, 2015)> survival through the post-common-envelope stage (Kostov et al., 2016a)> role of disk self-gravity in orbital evolution (Mutter et al., 2017a)> climate models (Wang & Cuntz, 2017)>
- Kepler-36** 2-planet system (rocky super-Earth and Neptune-like) near 7:6 mean motion resonance, with orbits differing by 10% but densities differing by a factor 8 with orbits differing by 10% but densities differing by a factor 8 discovery and evidence for migration (Carter et al., 2012)> chaotic orbits from proximity of 29:34 and first-order 6:7 resonances (Deck et al., 2012)> photo-evaporation versus core mass explains small size of inner planets (Lopez & Fortney, 2013)> system stability through dynamical modeling (Nagy & Ágas, 2013)> anti-correlated transit time variations (Ofir & Dreizler, 2013)> close spacing arises for wide range of migration parameters in turbulent disks (Paardekooper et al., 2013)> orbit tuning for convergent migration to bypass mean motion resonances into 7:6 resonance (Quillen et al., 2013)> effect of conjunctions on transit timing variations (Nesvorný & Vokrouhlický, 2014)> superrotating atmosphere in cyclostrophic balance (Peralta et al., 2014a)> constraints on the interior structure of planet b from mass and radius (Dorn et al., 2015)> compositional diversity between planets b and c due to giant impact devolatilisation (Liu et al., 2015f)> torques from an anisotropic evaporative wind, and evolution of resonant pairs (Teyssandier et al., 2015)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)> initial planet conditions from formation models (Owen & Morton, 2016)> close proximity planets and prospects for lithopanspermia (Steffen & Li, 2016)> composition and structure from mass-radius models (Unterborn et al., 2016)> reversibility error method applied to orbital dynamics (Panichi et al., 2017b)> dynamical studies focusing on grazing collisions, scatterings and mergers (Hwang et al., 2018a)>
- Kepler-37** 4-planet system; discovery of planets b, c, d, with inferred rocky nature of planet b (Barclay et al., 2013b)> planet d from transit timing (Hadden & Lithwick, 2014)> new data providing improved masses, sizes, and orbits (Marcy et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-38(AB)** circumbinary planet of Neptune-size; discovery (Orosz et al., 2012b)> habitable zone (Liu et al., 2013b)> rotational synchronisation and the habitable zone (Mason et al., 2013)> modeling, and sensitivity to disk structure (Kley & Haghighipour, 2014)> dynamical stability (Chavez et al., 2015)> analytic orbit propagation for circumbinary planets (Georgakarakos & Eggl, 2015)> survival through the post-common-envelope stage (Kostov et al., 2016a)>
- Kepler-39**  $18M_J$  planet; discovery and confirmation from radial velocity (Bouchy et al., 2011a)> photometry and new spectroscopy (South-



- worth, 2012)> tentative detection of planetary oblateness (Zhu et al., 2014b)> radial velocities from SOPHIE and HARPS-N (Bonomo et al., 2015)> limits on planet oblateness from transit depth variations (Biersteker & Schlichting, 2017)>
- Kepler-40** planet transiting evolved subgiant; discovery and confirmation from radial velocity (Bouchy et al., 2011a)> confirmation from radial velocity (Santerne et al., 2011b)> photometry and new spectroscopy (Southworth, 2011)> physical properties (Southworth, 2012)> improved masses, sizes, and orbits (Marcy et al., 2014)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)>
- Kepler-41** non-inflated hot Jupiter; confirmation from radial velocity, secondary transit from Kepler (Santerne et al., 2011a)> photometry and new spectroscopy (Southworth, 2012)> confirmation via phase curve analysis (Quintana et al., 2013)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)> atmospheric modeling, with westward phase shift of brightest region and substellar point explained by clouds (Shporer & Hu, 2015)>
- Kepler-42** 3-planet system orbiting low-metallicity high proper motion M dwarf; confirmation from statistics of multiple transits (Muirhead et al., 2012b)> rare example of short-period multi-planet system with close-proximity pairs (Steffen & Farr, 2013)> mapping of the interstellar medium (Johnson et al., 2015b)> star and planet parameters from Hawaii Infrared Parallax Program (Mann et al., 2017a)>
- Kepler-43** confirmation from radial velocity (Bonomo et al., 2012b)> photometry and new spectroscopy (Southworth, 2012)> radial velocities from HET-HRS (Endl et al., 2014)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> radial velocities from SOPHIE and HARPS-N (Bonomo et al., 2015)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)>
- Kepler-44** confirmation from radial velocity (Bonomo et al., 2012b)> photometry and new spectroscopy (Southworth, 2012)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> radial velocities from SOPHIE and HARPS-N (Bonomo et al., 2015)>
- Kepler-45** hot Jupiter orbiting M dwarf; photometry and new spectroscopy (Southworth, 2012)> confirmation from radial velocity, adaptive optics imaging, and near-infrared spectroscopy (Johnson et al., 2012b)> prograde versus retrograde motion from star spot transit timing (Holczer et al., 2015)>
- Kepler-46** 3-planet system; large transit time variations of planet b indicate non-transiting planet c, with transits of third candidate likely (Nesvorný et al., 2012)> confirmation of planet d from light curve (Rowe et al., 2014)> masses of planets b and c from transit timing variations (Saad-Olivera et al., 2017)>
- Kepler-47(AB)** 2-planet circumbinary system (first multiple planet system around a binary star), third planet unconfirmed; planets of  $3R_{\oplus}$  ( $P = 49$  d) and  $5R_{\oplus}$  ( $P = 303$  d, habitable zone) orbiting a  $P = 7.5$  d eclipsing binary; discovery and characterisation (Orosz et al., 2012a)> characterisation (Kostov et al., 2013)> determination of habitable zone (Kane & Hinkel, 2013)> determination of habitable zone (Liu et al., 2013b)> rotational synchronisation and the habitable zone (Mason et al., 2013)> climate modeling of habitable zone (Forgan, 2014)> stability regions in a multi-planet circumbinary system (Kratzer & Shannon, 2014)> multi-orbital ‘tight transits’, expected before 2025 (Liu et al., 2014b)> effects of X-ray and extreme ultraviolet radiation (Sanz-Forcada et al., 2014)> surface flux illumination and photosynthesis in circumbinary systems (Forgan et al., 2015)> third circumbinary planet could explain one anomalous transiting event (Hinse et al., 2015)> Milankovitch cycles in eccentricity, obliquity, and precession (Forgan, 2016)> survival through the post-common-envelope stage (Kostov et al., 2016a)> role of planet–planet scattering (Smullen et al., 2016)> habitability zones versus radiation and plasma environment (Zuluaga et al., 2016)>
- Kepler-48** 4-planet system, three transiting (bcd, planets b and c near 2:1 resonance), planet e from radial velocity; confirmation of planets b and c from correlated transit time variations and dynamical stability (Steffen et al., 2013)> new data confirming planet d, radial velocities for planet e, revised analysis of sizes and orbits (Marcy et al., 2014)> constraints on outer planets on inclined orbits (Read et al., 2017)> resonance chains explained through mass accretion and outward migration (Wang & Ji, 2017)>
- Kepler-49** 4-planet system, planets b and c near 3:2 resonance; confirmation of planets b and c from correlated transit time variations and dynamical stability (Steffen et al., 2013)> discovery of planets d and e from light curve analysis (Rowe et al., 2014)>
- Kepler-50** 2-planet system near 6:5 resonance; confirmation from correlated transit time variations and dynamical stability (Steffen et al., 2013)> asteroseismic obliquity determination (Chaplin et al., 2013)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-51** 3-planet system with planets b and c near 2:1 resonance; confirmation from correlated transit time variations and dynamical stability (Steffen et al., 2013)> three low-density planets suggested by transit time variations (Masuda, 2014)> planet d confirmed from light curve analysis (Rowe et al., 2014)>
- Kepler-52** 3-planet system with planets b and c near 2:1 resonance; confirmation of planets b and c from correlated transit time variations and dynamical stability (Steffen et al., 2013)> planet d from light curve analysis (Rowe et al., 2014)>
- Kepler-53** 3-planet system with planets b and c near 2:1 resonance; confirmation of planets b and c from correlated transit time variations and dynamical stability (Steffen et al., 2013)> planet d from light curve analysis (Rowe et al., 2014)> resonance chains explained through mass accretion and outward migration (Wang & Ji, 2017)>
- Kepler-54** 3-planet system with planets b and c near 2:1 resonance; confirmation of planets b and c from correlated transit time variations and dynamical stability (Steffen et al., 2013)> planet d from light curve analysis (Rowe et al., 2014)>
- Kepler-55** 5-planet system, planets b and c near 3:2 resonance; confirmation of planets b and c from transit time variations and dynamical stability (Steffen et al., 2013)> additional planets predicted from packed planetary systems hypothesis (Fang & Margot, 2012b)> debris disk observations from WISE (Lawler & Gladman, 2012)> discovery of planets d, e, f from light curves (Rowe et al., 2014)>
- Kepler-56** 3-planet system orbiting red giant ( $3.1R_{\odot}$ ), planet d non-transiting; planets b and c near 2:1 resonance, coplanar, but misaligned with stellar spin axis; planets b and c from correlated transit time variations and dynamical stability (Steffen et al., 2013)> large spin–orbit misalignment from asteroseismic analysis (Huber et al., 2013a)> eccentricities and densities from transit time variations (Hadden & Lithwick, 2014)> large observed obliquity consistent with dynamical origin rather than disk migration (Li et al., 2014d)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)> spin–orbit alignment from asteroseismology and confirmation as misaligned multi-planet system (Campante et al., 2016a)> transit time variations (Holczer et al., 2016)> confirmation from probabilities (Morton et al., 2016)> discovery, orbit and mass of planet d from radial velocity modelling (Otor et al., 2016)> inner system tilt due to outer planet scattering (Gratia & Fabrycky, 2017)> inner system tilt due to Lidov–Kozai oscillation (Mustill et al., 2017)>
- Kepler-57** 2-planets near 2:1 resonance; confirmation from correlated transit time variations and dynamical stability (Steffen et al., 2013)>
- Kepler-58** 3-planet system with planets b and c near 3:2 resonance; confirmation of planets b and c from correlated transit time variations and dynamical stability (Steffen et al., 2013)> planet d from light curve analysis (Rowe et al., 2014)>
- Kepler-59** 2-planets near 3:2 resonance; confirmation from correlated transit time variations and dynamical stability (Steffen et al., 2013)>
- Kepler-60** 3-planets near 5:4 (bc) and 4:3 (c:d) resonances; confirmation from correlated transit time variations and dynamical stability (Steffen et al., 2013)> tidal constraints from the 3-body resonance (Papaloizou, 2015)> nature and stability of the (generalised Laplace) 3-body resonance (Goździewski et al., 2016)> dynamical masses from transit time variations (Jontof-Hutter et al., 2016)> reversibility applied to orbital dynamics (Panichi et al., 2017b)>
- Kepler-61** stellar proxy modeling (Ballard et al., 2013)> host star properties of Kepler’s habitable planets (Armstrong et al., 2016b)>
- Kepler-62** 5-planet system (1.3, 0.5, 1.9, 1.6,  $1.4R_{\oplus}$ ), outer two in habitable zone; discovery (Borucki et al., 2013)> habitable zone  $H_2O$ -planet candidates (Kaltenegger et al., 2013)> lifetime of accompanying exomoons (Sasaki & Barnes, 2014)> model for tidally-evolving multiple systems using Mercury-T (Bolmont et al., 2015)> gravitational quantisation of orbits (Geroyannis, 2015)> host star properties of Kepler’s habitable planets (Armstrong et al., 2016b)> favourable for lightning-discharge studies during transit (Hodosan et al., 2016a)> orbital dynamics and mean motion resonances (Mia & Kushvah, 2016)> effect of orbital configuration on climate and habitability of planet f (Shields et al., 2016)> obliquity variations in planet f due to secular spin–orbit resonance (Deitrick et al., 2018)>

- Kepler-63** high obliquity from Rossiter–McLaughlin effect, anomalous transits from star spots (Sanchis-Ojeda et al., 2013c)> prograde versus retrograde motion from star spot transit timing (Holczer et al., 2015)> gyrochronology and isochrone ages (Maxted et al., 2015b)> stellar magnetic cycles (Estrela & Valio, 2016)>
- Kepler-64(AB)** PH-1 in NASA; transiting circumbinary planet in a quadruple (2+2) star system; discovery by Planet Hunters (Schwamb et al., 2013)> independent discovery (Kostov et al., 2013)> rotational synchronisation and the habitable zone (Mason et al., 2013)> climate modeling of habitable zone (Forgan, 2014)> dynamical stability (Chavez et al., 2015)> analytic orbit propagation for circumbinary planets (Georgakarakos & Eggl, 2015)> survival through the post-common-envelope stage (Kostov et al., 2016a)>
- Kepler-65** 3-planet system; confirmation and asteroseismic determination of obliquity (Chaplin et al., 2013)> superrotating atmosphere in cyclostrophic balance (Peralta et al., 2014a)> eccentricity from transit photometry (Van Eylen & Albrecht, 2015)>
- Kepler-66** in cluster NGC 6811; discovery, planets can form and survive in dense clusters (Meibom et al., 2013)> superrotating atmosphere in cyclostrophic balance (Peralta et al., 2014a)>
- Kepler-67** in cluster NGC 6811; discovery, planets can form and survive in dense clusters (Meibom et al., 2013)> superrotating atmosphere in cyclostrophic balance (Peralta et al., 2014a)>
- Kepler-68** 3-planet system, planet d non-transiting and discovered from radial velocity; confirmation and detection of planet d from radial velocity, and asteroseismology (Gilliland et al., 2013)> improved masses, sizes, and orbits (Marcy et al., 2014)> superrotating atmosphere in cyclostrophic balance (Peralta et al., 2014a)> stability of Earth-mass planets (Kane, 2015)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-69** 2-planet system, with  $1.7R_{\oplus}$  planet in habitable zone; confirmation via false positives (Barclay et al., 2013a)> planet c as likely super-Venus (Kane et al., 2013a)>
- Kepler-70** KOI-55 in NASA; 2-planet compact system orbiting post-red giant, hot pulsating B subdwarf; discovery from orbital brightness variations, survival through red giant phase (Charpinet et al., 2011)> low-frequency ‘reflection’ signals attributed to stellar pulsation (Krzesinski, 2015)>
- Kepler-71** KOI-217 in NASA; confirmation via false positives (Howell et al., 2010)> prograde versus retrograde motion from star spot transit timing (Holczer et al., 2015)>
- Kepler-72** in preparation
- Kepler-73** in preparation
- Kepler-74** confirmation from radial velocity (Hébrard et al., 2013a)> secondary eclipse and phase curves (Angerhausen et al., 2015a)> radial velocities from SOPHIE and HARPS-N (Bonomo et al., 2015)>
- Kepler-75** confirmation from radial velocity (Hébrard et al., 2013a)> radial velocities from SOPHIE and HARPS-N (Bonomo et al., 2015)>
- Kepler-76** listed in NASA with discovery method ‘orbital brightness modulation’; confirmation from beaming, ellipsoidal and reflection/emission modulations, BEER (Faigler et al., 2013)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)> Kepler phase curves with beaming, ellipsoidal, and reflection phase modulation (Faigler & Mazeh, 2015)>
- Kepler-77** discovery (Gandolfi et al., 2013)> radial velocities from HET-HRS (Endl et al., 2014)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> simple transit model (Ji et al., 2017)> eclipse, transit and occultation geometry at exo-syzygy (Veras & Breed, 2017)>
- Kepler-78**  $1.2R_{\oplus}$  rocky planet in 8.5-hr orbit; discovery, changing illumination from reflected and reprocessed light (Sanchis-Ojeda et al., 2013a)>  $\rho = 5.57 \text{ Mg m}^{-3}$  implying Fe and rock (Pepe et al., 2013a)> rocky planet nature (Howard et al., 2013)> slightly lower density (Hatzes, 2014a)> mass and density from stellar activity model (Grunblatt et al., 2015)> close-in orbit from Kozai–Lidov cycles (Rice, 2015)> magnetic properties of the host star (Moutou et al., 2016)>
- Kepler-79** compact 4-planet system with periods near a 1:2:4:6 chain (13.5–81.1 d); candidates inferred from multiplicity and transit timing variations (Steffen et al., 2010)> models of resonance formation (Wang et al., 2012b)> confirmation of planets b and c (Xie, 2013)> superrotating atmosphere in cyclostrophic balance (Peralta et al., 2014a)> discovery/confirmation of planets d and e from light curve analysis (Rowe et al., 2014)> dynamical analysis, stability, and formation (Jontof-Hutter et al., 2014)>
- Kepler-80** 6-planet system, with a 5-planet resonant chain; discovery of planets b and c (Xie, 2013)> discovery of planets d and e from light curve analysis (Rowe et al., 2014)> dynamical analysis (MacDonald et al., 2016)> planet f from light curve analysis (Morton et al., 2016)> planet g discovered through a convolutional neural network search (Shallue & Vanderburg, 2018)>
- Kepler-81** 3-planet system; discovery of planets b and c (Xie, 2013)> evidence for companion planets from transit timing variations (Steffen et al., 2010)> activity and differential stellar rotation (Savanov, 2011b)> differential stellar rotation (Reinhold et al., 2013)> discovery of planet d from light curve analysis (Rowe et al., 2014)> host star photometric variability and rotation from Kepler (Savanov & Dmitrienko, 2015b)>
- Kepler-82** 4-planet system; discovery of planets b and c (Xie, 2013)> d and e from light curve analysis (Rowe et al., 2014)>
- Kepler-83** 3-planet system; discovery of planets b and c (Xie, 2013)> discovery of planet d from light curve analysis (Rowe et al., 2014)>
- Kepler-84** 5-planet system; discovery of planets b and c (Xie, 2013)> discovery of d, e, f from light curve analysis (Rowe et al., 2014)>
- Kepler-85** 4-planet system; discovery of planets b and c (Xie, 2013)> confirmation via transit timing variations (Ming et al., 2013)> discovery of planets d and e from light curve analysis (Rowe et al., 2014)>
- Kepler-86** PH-2 in NASA; discovery (Wang et al., 2013a)> discounted exomoon candidate (Kipping et al., 2015a)> stellar companion from lucky imaging (Ginski et al., 2016a)>
- Kepler-87** 2-planet system including low density super-Earth; candidate (Ofir & Dreizler, 2013)> discovery (Ofir et al., 2014)> superrotating atmosphere in cyclostrophic balance (Peralta et al., 2014a)>
- Kepler-88** KOI-142 in NASA; 2-planet system, with planet c inferred from transit time variations; discovery (Nesvorný et al., 2013a)> confirmation of planet c from radial velocities (Barros et al., 2014b)> chaotic spin dynamics from large transit timing variations (Delisle et al., 2017)>
- Kepler-89** KOI-94 in NASA; 4-planet system, with planet–planet eclipse; radial velocities, planet d, and transit time variations (Weiss et al., 2013)> confirmation, Rossiter–McLaughlin effect, planet–planet eclipse (Hirano et al., 2012a)> transit time analysis, and prediction of next planet–planet eclipse (Masuda et al., 2013)> obliquity from Rossiter–McLaughlin effect (Albrecht et al., 2013)> superrotating atmosphere in cyclostrophic balance (Peralta et al., 2014a)>
- Kepler-90** KOI-351 in NASA; 8-planet system; planets d, e, and f are super-Earths close to mean motion resonance chain (2:3:4), planets b and c (both  $< 2R_{\oplus}$ ) within 0.5% of 4:5 mean motion resonance, planets g and h are gas giants with exceptional transit time variations (25.7h for planet g); identification of three planets (Batalha et al., 2013)> discovery of a further 4 planets, and system characterisation (Cabrera et al., 2014)> independent characterisation (Schmitt et al., 2014b)> possible exomoon is false positive (Kipping et al., 2015a)> planet i ( $P = 14 \text{ d}$ ) discovered through a convolutional neural network search (Shallue & Vanderburg, 2018)>
- Kepler-91** discovery (Lillo-Box et al., 2014c)> secondary eclipses and phase variations (Esteves et al., 2013)> radial velocity confirmation with Calar Alto–CAFE (Lillo-Box et al., 2014b)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> radial velocity observations and light curve noise modeling (Barclay et al., 2015a)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)> discarded Trojan planet candidate (Placek et al., 2015)> radial velocity observations with Subaru–HDS (Sato et al., 2015)> improved mass ratios (Budding et al., 2016a)> effect of dynamical tides excited by gravity waves in the host star on planet’s orbital evolution (Chernov et al., 2017)>
- Kepler-92** 3-planet system, planets b and c from transits, planet d from radial velocity; discovery (Xie, 2014b)> confirmation of planet d from transit time variations, and low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-93** 2-planet system; discovery of planet b through transits, planet c by radial velocity (Marcy et al., 2014)> asteroseismic study and 7 Spitzer transits lead to planet size uncertainty of 120 km (Ballard et al., 2014)> revised mass from 86 observations with HARPS-N and 32 archival Keck–HIRES (Dressing et al., 2015)> planet structure from stellar chemistry (Santos et al., 2015a)> core mass fraction from semi-empirical mass–radius relation for 2-layer rocky planets based

- on PREM (Zeng et al., 2016)> Bayesian analysis of interior structure using stellar abundance proxies (Dorn et al., 2017a)> application of scaling relations for rocky planet interiors (Zeng & Jacobsen, 2017)>
- Kepler-94** 2-planet system; discovery of planet b through transits, planet c by radial velocity (Marcy et al., 2014)>
- Kepler-95** discovery (Marcy et al., 2014)>
- Kepler-96** discovery (Marcy et al., 2014)>
- Kepler-97** 2-planet system; discovery of planet b through transits, planet c by radial velocity (Marcy et al., 2014)>
- Kepler-98** discovery (Marcy et al., 2014)>
- Kepler-99** discovery (Marcy et al., 2014)>
- Kepler-100** 3-planet system; discovery (Marcy et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)> resonance chains explained through mass accretion and outward migration (Wang & Ji, 2017)>
- Kepler-101** 2-planet system; discovery (Rowe et al., 2014)> confirmation with HARPS-N (Bonomo et al., 2014)>
- Kepler-102** 5-planet system; discovery (Marcy et al., 2014)> discovery characterisation (Wang et al., 2014b)>
- Kepler-103** 2-planet system; discovery (Marcy et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-104** 3-planet system; discovery (Rowe et al., 2014)>
- Kepler-105** 2-planet system; discovery (Wang et al., 2014b)> discovery and characterisation (Rowe et al., 2014)> difficulty explaining 4:3 mean motion resonance (Rein et al., 2012)>
- Kepler-106** 4-planet system; discovery (Marcy et al., 2014)>
- Kepler-107** 4-planet system; discovery (Rowe et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-108** 2-planet system; discovery (Rowe et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)> mutual inclination from transit time and transit duration analysis,  $\Delta i = 24^\circ$  (Mills & Fabrycky, 2017a)> system architecture inner system tilt due to Lidov-Kozai oscillation (Mustill et al., 2017)>
- Kepler-109** 2-planet system; discovery (Marcy et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-110** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-111** 2-planet system; discovery (Rowe et al., 2014)> additional planets predicted from packed planetary systems hypothesis (Fang & Margot, 2012b)>
- Kepler-112** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-113** 2-planet system; discovery (Marcy et al., 2014)>
- Kepler-114** 3-planet system; planet b (Rowe et al., 2014)> planets c and d (Xie, 2014b)>
- Kepler-115** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-116** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-117** 2-planet system; (Rowe et al., 2014)> joint photometric, spectroscopic, and dynamical analysis (Bruno et al., 2015)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)> masses and radii from photo-dynamical modeling (Almenara et al., 2015c)>
- Kepler-118** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-119** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-120** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-121** 2-planet system; discovery (Rowe et al., 2014)> additional planets predicted from packed planetary systems hypothesis (Fang & Margot, 2012b)>
- Kepler-122** 5-planet system; discovery of planets b, c, d, e (Rowe et al., 2014)> planet f from transit time variations (Hadden & Lithwick, 2014)>
- Kepler-123** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-124** 3-planet system; discovery (Rowe et al., 2014)>
- Kepler-125** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-126** 3-planet system; discovery (Rowe et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-127** 3-planet system; discovery (Rowe et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-128** 2-planet system; discovery (Xie, 2014b)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-129** 2-planet system; discovery (Rowe et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-130** 3-planet system; discovery (Rowe et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-131** 2-planet system; discovery (Marcy et al., 2014)>
- Kepler-132** 4-planet system; discovery (Rowe et al., 2014)> confirmation and planet e (Morton et al., 2016)>
- Kepler-133** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-134** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-135** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-136** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-137** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-138** 3-planet system; discovery of planet b (Rowe et al., 2014)> planets c and d, and search for exomoon (Kipping et al., 2014b)> Mars-sized mass of planet b from transit timing variations (Jontof-Hutter et al., 2015)> star and planet parameters from Hawaii Infrared Parallax Program (Mann et al., 2017a)> stellar chemical abundances for 13 elements (Souto et al., 2017)>
- Kepler-139...Kepler-144** 2- and 3-planet systems; discovery (Rowe et al., 2014)>
- Kepler-145** 2-planet system; discovery (Xie, 2014b)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-146** 2-planet system discovery (Rowe et al., 2014)>
- Kepler-147** 2-planet discovery (Rowe et al., 2014)>
- Kepler-148** 3-planet system; discovery of planets b and c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-149** 3-planet system; discovery (Rowe et al., 2014)>
- Kepler-150** 5-planet system; discovery (Rowe et al., 2014)> discovery of planet f (Schmitt et al., 2017)> independent discovery of planets b-e (Kunimoto et al., 2018)>
- Kepler-151** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-152** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-153** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-154** 5-planet system; discovery of planets b and c (Rowe et al., 2014)> candidate 6-planet system from independent light curve analysis (Ofir & Dreizler, 2013)> independent discovery of long-period candidate (Foreman-Mackey et al., 2016)> confirmation of planets b-from light curve analysis (Morton et al., 2016)>
- Kepler-155** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-156** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-157** 3-planet system; discovery of planets b and c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-158...Kepler-165** 2- and 3-planet systems; discovery (Rowe et al., 2014)>
- Kepler-166** 3-planet system; discovery of planets b and c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-167** 4-planet system, with planet e being a first transiting Jupiter analogue ( $R_p = 0.9R_J$ ,  $e = 0.06$ ,  $P = 2.9$  yr,  $T_{eq} = 131$  K); discovery (Rowe et al., 2014)> independent discovery of planet e (Foreman-Mackey et al., 2016)> nature of planet e (Kipping et al., 2016)>
- Kepler-168...Kepler-173** 2-, 3-, 4-, and 5-planet systems; discovery (Rowe et al., 2014)> Amongst these:  
Kepler-170: dynamical rearrangement of super-Earths during disk dispersal by magnetospheric rebound (Liu et al., 2017a)>
- Kepler-174** 3-planet system; discovery (Rowe et al., 2014)> host star properties of Kepler's habitable planets (Armstrong et al., 2016b)>
- Kepler-175** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-176** 4-planet system; discovery of planets b-d (Rowe et al., 2014)> discovery of planet e (Morton et al., 2016)>
- Kepler-177** 2-planet system; discovery (Xie, 2014b)> dynamical masses from transit time variations (Jontof-Hutter et al., 2016)>
- Kepler-178** 3-planet system; discovery (Rowe et al., 2014)>
- Kepler-179** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-180** 2-planet system; discovery (Rowe et al., 2014)> dynamical rearrangement of super-Earths during disk dispersal by magnetospheric rebound (Liu et al., 2017a)>
- Kepler-181** 2-planet system; discovery (Rowe et al., 2014)> difficulty explaining 4:3 mean motion resonance (Rein et al., 2012)>
- Kepler-182** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-183** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-184** 3-planet system; discovery (Rowe et al., 2014)>

- Kepler-185** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-186** 5-planet system, all roughly Earth-sized; discovery of planets b, c, d, e (Rowe et al., 2014)> planet f ( $1.1R_{\oplus}$ ) in habitable zone, from additional year of Kepler data (Quintana et al., 2014)> formation, tidal evolution, habitability (Bolmont et al., 2014)> mapping of the interstellar medium (Johnson et al., 2015b)> confirmed statistical validation of planet f, BLENDER (Torres et al., 2015)> host star properties of Kepler's habitable planets (Armstrong et al., 2016b)> favourable for lightning-discharge studies during transit (Hodosán et al., 2016a)> variable incident flux due to obliquity and eccentricity (Kane & Torres, 2017)> stellar chemical abundances for 13 elements (Souto et al., 2017)>
- Kepler-187...Kepler-190** 2-planet systems; discovery (Rowe et al., 2014)>
- Kepler-191** 3-planet system; discovery of planets b–c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-192** 3-planet system; discovery of planets b–c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)> resonance chains explained through mass accretion and outward migration (Wang & Ji, 2017)>
- Kepler-193...Kepler-196** 2- and 3-planet systems; discovery (Rowe et al., 2014)>
- Kepler-197** 4-planet system; discovery (Rowe et al., 2014)> eccentricity from transit photometry (Van Eylen & Albrecht, 2015)>
- Kepler-198** 3-planet system; discovery of planets b–c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-199...Kepler-207** 2-, 3-, and 4-planet systems; discovery (Rowe et al., 2014)>
- Kepler-208** 4-planet system; discovery (Rowe et al., 2014)> additional single transits (Schmitt et al., 2017)>
- Kepler-209** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-210** 2-planet system; discovery (Rowe et al., 2014)> short-period Neptune-size planets around active host star (Ioannidis et al., 2014)> spot evolution and differential rotation (Ioannidis & Schmitt, 2016)>
- Kepler-211** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-212** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-213** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-214** 2-planet system; discovery (Rowe et al., 2014)> new long-period candidate (Foreman-Mackey et al., 2016)>
- Kepler-215** 4-planet system; discovery (Rowe et al., 2014)>
- Kepler-216** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-217** 3-planet system; discovery of planets b–c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-218** 3-planet system; discovery of planets b–c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-219** 3-planet system; discovery (Rowe et al., 2014)>
- Kepler-220** 4-planet system; discovery (Rowe et al., 2014)> additional candidates from light curve analysis (Ofir & Dreizler, 2013)>
- Kepler-221** 4-planet system; discovery (Rowe et al., 2014)>
- Kepler-222** 3-planet system; discovery (Rowe et al., 2014)>
- Kepler-223** 4-planet system in a 3:4:6:8 resonant chain; discovery (Rowe et al., 2014)> chain of first-order resonances: period ratios 3:4:6:8 to within  $10^{-3}$  (Fabrycky et al., 2011); orbit-crossing planetesimals (Moore et al., 2013)> migration models yield order of multi-planet resonant capture (Delisle, 2017)>
- Kepler-224** 4-planet system; discovery (Rowe et al., 2014)>
- Kepler-225** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-226** 3-planet system; discovery (Rowe et al., 2014)> difficulty explaining 4:3 mean motion resonance (Rein et al., 2012)>
- Kepler-227...Kepler-231** 2- and 3-planet systems; discovery (Rowe et al., 2014)>
- Kepler-232** 2-planet system; discovery (Rowe et al., 2014)> difficulty explaining 4:3 mean motion resonance (Rein et al., 2012)>
- Kepler-233...Kepler-237** 2-, 3-, and 4-planet systems; discovery (Rowe et al., 2014)>
- Kepler-238** 5-planet system; discovery of planets b, c, d (Rowe et al., 2014)> planets e and f (Xie, 2014b)> migration and trapping in the 4:2:1 mean motion resonance (Sun et al., 2017b)>
- Kepler-239...Kepler-244** 2- and 3-planet systems; discovery (Rowe et al., 2014)>
- Kepler-245** 4-planet system; discovery of planets b–c (Rowe et al., 2014)> discovery of planets d–e (Morton et al., 2016)>
- Kepler-246** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-247** 3-planet system; discovery of planets b and c (Rowe et al., 2014)> outer non-transiting candidate from transit time variations (Nesvorný et al., 2014a)> effect of conjunctions on transit timing variations (Nesvorný & Vokrouhlický, 2014)>
- Kepler-248** 2-planet system; discovery (Rowe et al., 2014)> evidence for companion planets from transit timing variations (Steffen et al., 2010)> activity and differential stellar rotation (Savanov, 2011b)> differential stellar rotation (Reinhold et al., 2013)> stellar variability and rotation from Kepler (Savanov & Dmitrienko, 2015b)>
- Kepler-249** 3-planet system; discovery (Rowe et al., 2014)>
- Kepler-250** 3-planet system; discovery (Rowe et al., 2014)>
- Kepler-251** 4-planet system; discovery (Rowe et al., 2014)>
- Kepler-252** 2-planet system; discovery (Rowe et al., 2014)> presence and origin of high-order harmonics in Kepler light curves (Armstrong & Rein, 2015)>
- Kepler-253** 3-planet system; discovery (Rowe et al., 2014)>
- Kepler-254** 3-planet system; discovery (Rowe et al., 2014)>
- Kepler-255** 3-planet system; discovery of planets b–c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-256...Kepler-260** 2-, 3-, and 4-planet systems; discovery (Rowe et al., 2014)>
- Kepler-261** 2-planet system; discovery (Rowe et al., 2014)> measurement of stellar inclination (Hirano et al., 2014)>
- Kepler-262...Kepler-270** 2-, 3-, and 4-planet systems; discovery (Rowe et al., 2014)>
- Kepler-271** 3-planet system; discovery of planets b–c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-272...Kepler-275** 2- and 3-planet systems; discovery (Rowe et al., 2014)> gravitational quantisation of orbits (Geroyannis, 2015)>
- Kepler-276** 3-planet system; discovery of planet b (Rowe et al., 2014)> planets c, d (Xie, 2014b)>
- Kepler-277** 2-planet system; discovery (Xie, 2014b)>
- Kepler-278** 2-planet system; discovery (Rowe et al., 2014)> low eccentricity from transit duration (Van Eylen & Albrecht, 2015)>
- Kepler-279** 3-planet system; discovery of planet b (Rowe et al., 2014)> confirmation via transit timing variations (Ming et al., 2013)> planets c and d (Xie, 2014b)>
- Kepler-280** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-281** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-282** 4-planet system; discovery of planets b and c (Rowe et al., 2014)> planets d and e (Xie, 2014b)>
- Kepler-283** 2-planet system; discovery (Rowe et al., 2014)> host star properties of Kepler's habitable planets (Armstrong et al., 2016b)>
- Kepler-284...Kepler-288** 2-, 3-, and 4-planet systems; discovery (Rowe et al., 2014)>
- Kepler-289** 3-planet system; discovery of planets b and c (Rowe et al., 2014)> planet d (Schmitt et al., 2014a)>
- Kepler-290...Kepler-295** 2-, 3-, 4-, 5-planet systems; discovery (Rowe et al., 2014)>
- Kepler-296** 5-planet circumprimary system; discovery (Rowe et al., 2014)> planets orbit the primary star (Barclay et al., 2015b)> confirmed statistical validation of planets e and f, BLENDER (Torres et al., 2015)> host star properties of Kepler's habitable planets (Armstrong et al., 2016b)>
- Kepler-297** 2-planet system; discovery (Rowe et al., 2014)> resonance chains explained through mass accretion and outward migration (Wang & Ji, 2017)>
- Kepler-298** 3-planet system; discovery (Rowe et al., 2014)> host star properties of Kepler's habitable planets (Armstrong et al., 2016b)>
- Kepler-299** 4-planet system; discovery (Rowe et al., 2014)>
- Kepler-300** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-301** 3-planet system; discovery (Rowe et al., 2014)>
- Kepler-302** 2-planet system; discovery (Rowe et al., 2014)> migration and trapping in the 4:2:1 mean motion resonance (Sun et al., 2017b)>
- Kepler-303** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-304** 4-planet system; discovery of planets b–d (Rowe et al., 2014)> discovery of planet e (Morton et al., 2016)>

- Kepler-305** 3-planet system; discovery of planets b and c (Xie, 2014b)> confirmation via transit timing variations (Ming et al., 2013)> planet d (Rowe et al., 2014)>
- Kepler-306** 4-planet system; discovery (Rowe et al., 2014)>
- Kepler-307** 2-planet system; discovery (Xie, 2014b)> dynamical masses from transit time variations (Jontof-Hutter et al., 2016)>
- Kepler-308** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-309** 2-planet system; discovery (Rowe et al., 2014)> additional planets predicted from packed planetary systems hypothesis (Fang & Margot, 2012b)>
- Kepler-310...Kepler-327** 2- and 3-planet systems; discovery (Rowe et al., 2014)>
- Kepler-328** 2-planet system; discovery (Xie, 2014b)>
- Kepler-329...Kepler-337** 2- and 3-planet systems; discovery (Rowe et al., 2014)>
- Kepler-338** 4-planet system; discovery of planets b, c, d (Rowe et al., 2014)> planet e (Hadden & Lithwick, 2014)> eccentricity from transit photometry (Van Eylen & Albrecht, 2015)>
- Kepler-339** 3-planet system; discovery (Rowe et al., 2014)>
- Kepler-340** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-341** 4-planet system; discovery (Rowe et al., 2014)>
- Kepler-342** 4-planet system; discovery of planets b–d (Rowe et al., 2014)> discovery of planet e (Morton et al., 2016)>
- Kepler-343...Kepler-349** 2-planet systems; discovery (Rowe et al., 2014)>
- Kepler-350** 3-planet system; discovery of planet b (Rowe et al., 2014)> planets c and d (Xie, 2014b)>
- Kepler-351** 3-planet system; discovery of planets b–c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-352...Kepler-395** 2-, 3-planet systems; discovery (Rowe et al., 2014)>
- Kepler-396** 2-planet system; discovery (Xie, 2014b)> confirmation via transit timing variations (Ming et al., 2013)>
- Kepler-397** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-398** 3-planet system; discovery of planets b–c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-399** 3-planet system; discovery (Rowe et al., 2014)> resonance chains explained through mass accretion and outward migration (Wang & Ji, 2017)>
- Kepler-400** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-401** 3-planet system; discovery of planets b–c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-402** 4-planet system; discovery (Rowe et al., 2014)>
- Kepler-403** 3-planet system; discovery of planets b–c (Rowe et al., 2014)> discovery of planet d (Morton et al., 2016)>
- Kepler-404** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-405** 2-planet system; discovery (Rowe et al., 2014)>
- Kepler-406** 2-planet system; discovery (Marcy et al., 2014)>
- Kepler-407** 2-planet system; planet b discovered from transits, planet d from radial velocity (Marcy et al., 2014)>
- Kepler-408** discovery (Marcy et al., 2014)>
- Kepler-409** discovery (Marcy et al., 2014)>
- Kepler-410A** confirmation through asteroseismology, adaptive optics imaging, and Spitzer, and transit timing variations (Van Eylen et al., 2014)> transit timing variations (Mazeh et al., 2013)> TTVs and properties of the perturbing body (Gajdoš et al., 2017)>
- Kepler-411** 2-planet system; discovery of planet b (Wang et al., 2014b)> discovery of planet c (Morton et al., 2016)>
- Kepler-412** discovery, and combination with radial velocities from SOPHIE (Deleuil et al., 2014)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)>
- Kepler-413(AB)** circumbinary planet orbiting eclipsing binary system, with sections of hundreds of days without transits from precession; discovery (Kostov et al., 2014)> dynamical stability (Chavez et al., 2015)> analytic orbit propagation for circumbinary planets (Georgakarakos & Eggl, 2015)> scattering of circumbinary planets to explain the orbital configuration (Gong & Ji, 2017)> dynamical stability confined by 6:1 and 7:1 mean motion resonances (Popova, 2017)> climate models (Wang & Cuntz, 2017)>
- Kepler-414** 2-planet system; discovery from transit time variations (Hadden & Lithwick, 2014)>
- Kepler-415** 2-planet system; discovery from transit time variations (Hadden & Lithwick, 2014)>
- Kepler-416** 2-planet system; discovery from transit time variations (Hadden & Lithwick, 2014)>
- Kepler-417** 2-planet system; discovery from transit time variations (Hadden & Lithwick, 2014)>
- Kepler-418** discovery/confirmation based on transit colour signature (Tingley et al., 2014)>
- Kepler-419** 2-planet hot Jupiter system; discovery of planet b from transits and planet c from transit time variations (Dawson et al., 2012)> planet characterisation from transit time variations, with low mutual inclination,  $\Delta = 9^\circ$  (Dawson et al., 2014)>
- Kepler-420** KOI-1257 in NASA; long-period (87 d) high eccentricity (0.77) orbit; confirmation from SOPHIE and Rossiter–McLaughlin effect (Santerne et al., 2014)> climate models (Wang & Cuntz, 2017)>
- Kepler-421** near circular orbit near snow line ( $P = 704$  d); discovery (Kipping et al., 2014c)> no timing variations in third observed transit (Dalba & Muirhead, 2016)> new long-period candidate (Foreman-Mackey et al., 2016)>
- Kepler-422** discovery/confirmation from HET-HRS (Endl et al., 2014)>
- Kepler-423** discovery and confirmation from HET-HRS (Endl et al., 2014)> radial velocities from NOT-FIES (Gandolfi et al., 2015)> use as a precision clock to constrain time variation of the gravitational constant (Masuda & Suto, 2016)>
- Kepler-424** 2-planet system; discovery of planet b from transits, planet c from radial velocity with HET-HRS (Endl et al., 2014)>
- Kepler-425** discovery and confirmation with SOPHIE and HARPS-N (Hébrard et al., 2014b)>
- Kepler-426** discovery and confirmation with SOPHIE and HARPS-N (Hébrard et al., 2014b)>
- Kepler-427** discovery and confirmation with SOPHIE and HARPS-N (Hébrard et al., 2014b)> precession period and planet oblateness from transit depth variations (Biersteker & Schlichting, 2017)>
- Kepler-428** discovery and confirmation with SOPHIE and HARPS-N (Hébrard et al., 2014b)>
- Kepler-429** KIC-10001893 in NASA; 3-planet system orbiting post-red giant, hot B subdwarf; discovery from pulsation frequency modulation (Silvotti et al., 2014)>
- Kepler-430** 2-planet system; discovery and high resolution multicolour imaging (Everett et al., 2015)>
- Kepler-431** 3-planet system; discovery and high resolution multicolour imaging (Everett et al., 2015)>
- Kepler-432** 2-planet system, planet b discovered from transits, planet c from radial velocity; confirmation of planet b from CAHA-CAFE (Ciceri et al., 2015a)> further analysis of CAHA-CAFE radial velocities (Ortiz et al., 2015b)> independent discovery of planet b, discovery of planet c, asteroseismic oscillations of host star (Quinn et al., 2015)>
- Kepler-433** validation with SOPHIE (Almenara et al., 2015b)>
- Kepler-434** grazing transit; validation with SOPHIE (Almenara et al., 2015b)>
- Kepler-435** validation with SOPHIE (Almenara et al., 2015b)>
- Kepler-436** 2-planet system; statistical validation of planet b, BLENDER (Torres et al., 2015)> discovery of planet c (Morton et al., 2016)>
- Kepler-437** statistical validation, BLENDER (Torres et al., 2015)> mapping of the interstellar medium (Johnson et al., 2015b)>
- Kepler-438** statistical validation, BLENDER (Torres et al., 2015)> star properties of Kepler's habitable planets (Armstrong et al., 2016b)>
- Kepler-439** statistical validation, BLENDER (Torres et al., 2015)> validation with multicolour transit photometry (Colón et al., 2015)>
- Kepler-440** statistical validation, BLENDER (Torres et al., 2015)> star properties of Kepler's habitable planets (Armstrong et al., 2016b)>
- Kepler-441** statistical validation, BLENDER (Torres et al., 2015)>
- Kepler-442** statistical validation, BLENDER (Torres et al., 2015)> star properties of Kepler's habitable planets (Armstrong et al., 2016b)>
- Kepler-443** statistical validation, BLENDER (Torres et al., 2015)> star properties of Kepler's habitable planets (Armstrong et al., 2016b)>

- Kepler-444** 5-planet system around primary (Kepler-444A) of a metal-poor triple star with age  $11.2 \pm 1.0$  Gyr; discovery (Campante et al., 2015)> mapping of the interstellar medium (Johnson et al., 2015b)> confirmation from transit time variations (Van Eylen & Albrecht, 2015)> unresolved pair of M dwarfs (Kepler-444BC) at 66 au, and constraints on co-planarity, disk truncation, and formation (Dupuy et al., 2016)> migration times from formation models (Papaloizou, 2016)> eclipse, transit and occultation geometry at exo-syzygy (Veras & Breedt, 2017)> Ly- $\alpha$  variations from the host star (Bourrier et al., 2017c)> transit timing variations and masses of planets d and e (Mills & Fabrycky, 2017b)>
- Kepler-445** 3-planet system; confirmation by high contrast imaging with Keck-NIRC2 (Muirhead et al., 2015)> revised transit depth from Lowell-DCT identified Kepler results contaminated by stellar crowding (Dalba et al., 2017)> star and planet parameters from Hawaii Infrared Parallax Program (Mann et al., 2017a)>
- Kepler-446** 3-planet system, metal-poor M dwarf with high space velocity; confirmation by high contrast imaging with Keck-NIRC2 (Muirhead et al., 2015)>
- Kepler-447** grazing transit; discovery from radial velocity with Calar Alto-CAFE (Lillo-Box et al., 2015)>
- Kepler-448** KOI-12 in NASA; discovery, radial velocity and line-profile tomography with SOPHIE (Bourrier et al., 2015a)> Rossiter-McLaughlin effect (Johnson et al., 2017c)> eccentric companion from transit timing and transit duration variations (Masuda, 2017)>
- Kepler-449** 2-planet system; discovery from transit time variations (Van Eylen & Albrecht, 2015)>
- Kepler-450** 3-planet system; discovery from transit time variations (Van Eylen & Albrecht, 2015)> resonance chains explained through mass accretion and outward migration (Wang & Ji, 2017)>
- Kepler-451** 2MASS J19383260+4603591 in NASA; listed in NASA with discovery method 'eclipse timing variations'; periodic variation in timing signal attributed to  $1.9M_J$  planet in the sdB+M dwarf binary system 2M J1938+4603 (Baran et al., 2015b)> pre-discovery of a multimode pulsating sdB star with an eclipsing dM companion (Østensen et al., 2010)> Römer delay and binary mass ratio (Barlow et al., 2012)>
- Kepler-452** Earth-like exoplanet in the habitable zone of a Sun-like star; discovery, and Earth-like properties (Jenkins et al., 2015)> estimates of surface habitability (Silva et al., 2017)> climate and habitability from coupled atmosphere-ocean GCM (Hu et al., 2017)>
- Kepler-453(AB)** 10th Kepler circumbinary planet; discovery (Welsh et al., 2015)> habitability zones versus radiation and plasma environment (Zuluaga et al., 2016)>
- Kepler-454** 2-planet system, planet b discovered from transits, planet c from radial velocity; discovery (Gettel et al., 2016)>
- Kepler-455** KIC-3558849 in NASA; discovery by Planet Hunters (Wang et al., 2015a)>
- Kepler-456** KIC-5951458 in NASA; discovery by Planet Hunters (Wang et al., 2015a)>
- Kepler-457** KOI-7892 in NASA; 2-planet system; discovery by Planet Hunters (Wang et al., 2015a)>
- Kepler-458** KIC-9663113 in NASA; 2-planet system; discovery by Planet Hunters (Wang et al., 2015a)>
- Kepler-459** KIC-10525077 in NASA; discovery by Planet Hunters (Wang et al., 2015a)>
- Kepler-460** KIC-5437945 in NASA; 2-planet system; discovery by Planet Hunters (Wang et al., 2015a)>
- Kepler-461** confirmation from false-positive probabilities (Morton et al., 2016)>
- Kepler-462** confirmation from false-positive probabilities (Morton et al., 2016)> possible 2-planet system, and constraints on spin-orbit misalignments (Ahlers et al., 2015)>
- Kepler-463...Kepler-480** 1- and 2-planet systems from false-positive probabilities (Morton et al., 2016)>
- Kepler-481** confirmation from false-positive probabilities (Morton et al., 2016)> evidence for companion planet(s) from transit timing variations (Steffen et al., 2010)>
- Kepler-482** confirmation from false-positive probabilities (Morton et al., 2016)>
- Kepler-483** confirmation from false-positive probabilities (Morton et al., 2016)>
- Kepler-484** confirmation from false-positive probabilities (Morton et al., 2016)>
- Kepler-485** confirmation from false-positive probabilities (Morton et al., 2016)> exomoon candidate from excess photometric transit scatter (Szabó et al., 2013)>
- Kepler-486** confirmation from false-positive probabilities (Morton et al., 2016)>
- Kepler-487** 2-planet system from false-positive probabilities (Morton et al., 2016)> multiple transiting candidates (Steffen et al., 2010)>
- Kepler-488...Kepler-491** confirmation from false-positive probabilities (Morton et al., 2016)>
- Kepler-492** discovery (Díaz et al., 2013)> radial velocities from SOPHIE and HARPS-N (Bonomo et al., 2015)> confirmation (Morton et al., 2016)>
- Kepler-493...Kepler-538** 1- and 2-planet systems from false-positive probabilities (Morton et al., 2016)>
- Kepler-539** 2-planet system; discovery of planet b (Morton et al., 2016)> discovery of planet c (Mancini et al., 2016c)>
- Kepler-540...Kepler-559** 1- and 2-planet systems from false-positive probabilities (Morton et al., 2016)> A few Kepler-NNN are absent from this sequence Amongst these: Kepler-553: additional planets predicted from packed planetary systems hypothesis (Fang & Margot, 2012b)>
- Kepler-560** confirmation from false-positive probabilities (Morton et al., 2016)> star and planet parameters from Hawaii Infrared Parallax Program (Mann et al., 2017a)>
- Kepler-561...Kepler-761** 1- and 2-planet systems from false-positive probabilities (Morton et al., 2016)> with higher multiplicities in the cases of Kepler-603(3), and Kepler-758(4). Amongst these: Kepler-598: additional planets predicted from packed planetary systems hypothesis (Fang & Margot, 2012b)> Kepler 635: transit signals hidden in the intrinsic stellar pulsations (Sowicka et al., 2017)> Kepler-656: validation with multicolour transit photometry (Colón et al., 2015)> Kepler-693: eccentric companion from transit timing and transit duration variations (Masuda, 2017)> Kepler-718: exomoon candidate from photometric transit scatter (Szabó et al., 2013)> Kepler-736: debris disk from WISE (Lawler & Gladman, 2012)>
- Kepler-762** discovery from false-positive probabilities (Morton et al., 2016)> prograde versus retrograde motion from star spot transit timing (Holczer et al., 2015)> phase modulation due to beaming, ellipsoidal effect and reflection (Lillo-Box et al., 2016c)>
- Kepler-763...Kepler-973** 1- and 2-planet systems from false-positive probabilities (Morton et al., 2016)> with higher multiplicities in the cases of Kepler-770(3). Amongst these: Kepler-767: debris disk from WISE (Lawler & Gladman, 2012)> Kepler-770: new long-period candidate (Foreman-Mackey et al., 2016)> Kepler-891: debris disk from WISE (Lawler & Gladman, 2012)>
- Kepler-974** confirmation of planet b from false-positive probabilities,  $p = 4.1$  d (Morton et al., 2016)> unconfirmed  $P = 4.24$  h candidate KOI-1843.03 (Ofir & Dreizler, 2013)> Roche limit for unconfirmed candidate KOI-1843.03 (Rappaport et al., 2013)>
- Kepler-975...Kepler-1003** 1- and 2-planet systems from false-positive probabilities (Morton et al., 2016)> Amongst these: Kepler-989: new long-period candidate (Foreman-Mackey et al., 2016)>
- Kepler-1004** confirmation from false-positive probabilities (Morton et al., 2016)> radial velocities from Subaru-HDS (Sato et al., 2015)>
- Kepler-1005...Kepler-1114** 1- and 2-planet systems from false-positive probabilities (Morton et al., 2016)>
- Kepler-1115** discovery from false-positive probabilities (Morton et al., 2016)> second super-Earth with a measured spin-orbit alignment (after 55 Cnc e), determined from rotational gravity darkening, and the first which is aligned (Barnes et al., 2015a)>
- Kepler-1116...Kepler-1318** 1- and 2-planet systems from false-positive probabilities (Morton et al., 2016)> with higher multiplicities in the case of Kepler-1254(3).
- Kepler-1319** discovery and confirmation from false-positive probabilities (Morton et al., 2016)> star and planet parameters from Hawaii Infrared Parallax Program (Mann et al., 2017a)>

- Kepler-1320...Kepler-1516** 1- and 2-planet systems from false-positive probabilities (Morton et al., 2016)> with higher multiplicities in the case of Kepler-1388(4)
- Kepler-1517** confirmation from false-positive probabilities (Morton et al., 2016)> phase modulation due to beaming, ellipsoidal effect and reflection (Lillo-Box et al., 2016c)>
- Kepler-1518** confirmation from false-positive probabilities (Morton et al., 2016)>
- Kepler-1519** confirmation from false-positive probabilities (Morton et al., 2016)>
- Kepler-1520** ≡ KIC-12557548; disintegrating short-period Mercury-size planet; discovery (Rappaport et al., 2012)> evidence for disintegration from detailed transit modeling (Brogi et al., 2012a)> comet-like tail from light curve analysis (Budaj, 2013)> star spot versus transit depth relation (Kawahara et al., 2013)> implications from implied catastrophic evaporation (Perez-Becker & Chiang, 2013)> multi-wavelength observations with HST-WFC3, Keck, CFHT-WIRCam (Croll et al., 2014)> light curve analysis (Budaj, 2014)> search for circumplanetary material and orbital period variations (Garai et al., 2014)> analysis of 15 quarters of Kepler data (van Werkhoven et al., 2014a)> constraints on dust composition (van Lieshout et al., 2014)> direct evidence for an evolving dust cloud from ULTRACAM (Bochinski et al., 2015)> relation between transit depths and stellar rotation period (Croll et al., 2015b)> size and composition of dust grains, and mass loss rate, from light curve (van Lieshout et al., 2016)> transit profile in the context of artificial megastructures (Wright et al., 2016b)>
- Kepler-1521...Kepler-1624** 1- and 2-planet systems from false-positive probabilities (Morton et al., 2016)> with higher multiplicities in the case of Kepler-1542(4)
- Kepler-1625** confirmation from false-positive probabilities (Morton et al., 2016)> exomoon candidate from phase-folded transit light curve (Teachey et al., 2018)>
- Kepler-1626...Kepler-1646** 1- and 2-planet systems from false-positive probabilities (Morton et al., 2016)>
- Kepler-1647(AB)** long-period (1100-d) transiting circumbinary; planet displays three transits in the Kepler light curve, one during an eclipse creating a syzygy; discovery (Kostov et al., 2016b)> survival through the post-common-envelope stage (Kostov et al., 2016a)> climate models (Wang & Cuntz, 2017)>
- Kepler-1648** KIC-7917485 in NASA;  $12M_j$ ,  $P = 840$  d,  $e = 0.15$ ; discovery from pulsational phase shifts in the host A star induced by orbital motion (Murphy et al., 2016)>
- Kepler-1649** discovery (Angelo et al., 2017)>
- Kepler-1650** discovery and confirmation from transit timing variations (Holczer et al., 2016)> star and planet parameters from Hawaii Infrared Parallax Program (Mann et al., 2017a)>
- Kepler-1651** discovery and confirmation from transit timing variations (Holczer et al., 2016)> nearby star from lucky imaging (Wöllert et al., 2015)> star and planet parameters from Hawaii Infrared Parallax Program (Mann et al., 2017a)>
- Kepler-1652** discovery and confirmation from transit timing variations (Holczer et al., 2016)> confirmation from optical/near-infrared spectroscopy and high-resolution imaging (Torres et al., 2017)>
- Kepler-1653** discovery and confirmation from transit timing variations (Holczer et al., 2016)> confirmation from optical/near-infrared spectroscopy and high-resolution imaging (Torres et al., 2017)>

## KIC

(identifiers used as default alias in NASA Exoplanet Archive)

- KIC-3558849** see Kepler-455
- KIC-5437945** see Kepler-460
- KIC-5951458** see Kepler-456
- KIC-7917485** see Kepler-1648
- KIC-8462852** Boyajian's star: not an exoplanet candidate, but may host exocomets or other disrupted bodies; discovery by Planet Hunters from irregular flux dips up to 20% (Boyajian et al., 2016)> NASA-IRTF flux consistent with giant comet (Lisse et al., 2015)> infrared limits from Spitzer-IRAC (Marengo et al., 2015)> search for optical flashes from archival VERITAS data 2009-15 (Abeysekara et al., 2016)> tidally-disrupted comet interpretation (Bodman & Quillen, 2016)> statistical accuracy of Harvard plates (Hippke et al.,

2016)> limits on radio flux between 1-10GHz from ATA (Harp et al., 2016a)> Gaia distance consistent with spectral type (Hippke & Angerhausen, 2016)> systematic fading during Kepler mission (Montet & Simon, 2016)> photometry/astrometry consistent with comet/planetoid swarm (Makarov & Goldin, 2016a)> century-long dimming from Harvard plate archive (Schaefer, 2016)> limits on optical SETI pulses from Boquete Observatory, Panama (Schuetz et al., 2016)> constraints on circumstellar dust from SCUBA-2 (Thompson et al., 2016)> transit profile in the context of artificial megastructures (Wright et al., 2016b)> classification of light curve explanations (Wright & Sigurdsson, 2016)> constancy of plates from Sonneberg 1934-95 and Sternberg 1895-1995 (Hippke et al., 2017)> dips could be explained by circumsolar (solar system) rings (Katz, 2017)> repeated transit signature at 928-d period, with next event 2019 October 3-8 (Kiefer et al., 2017)> review of known properties (Ksanfomality, 2017)> criticism of cometary hypothesis (Ksanfomality & Tavrov, 2017)> secular dimming attributed to inspiral of a planetary body (Metzger et al., 2017)> explanation as four dust-enshrouded objects (Neslušan & Budaj, 2017)> explanation as tilted exoring disturbed by a close third companion (Sucerquia et al., 2017)> explanation as large ringed body with a swarm of associated Trojans (Ballesteros et al., 2018)> explanation as brown dwarf and associated ring system in 1601-d elliptical orbit (Bourne et al., 2018)> ultraviolet variability from GALEX (Davenport et al., 2018)> secular dimming from 800/4000-d photometric monitoring from ASAS-SN/ASAS (Simon et al., 2018)> reassessment of families of solutions (Wright, 2018)> explanation as circumstellar material (e.g. exocomets) in a single elliptical orbit (Wyatt et al., 2018)>

**KIC-9663113** see Kepler-458**KIC-10001893** see Kepler-429**KIC-10525077** see Kepler-459

## KOI

(identifiers used as default alias in NASA Exoplanet Archive)

**KOI-12** see Kepler-448**KOI-13** see Kepler-13**KOI-55** see Kepler-70**KOI-94** see Kepler-89**KOI-142** see Kepler-88**KOI-217** see Kepler-71**KOI-351** see Kepler-90**KOI-1257** see Kepler-420**KOI-7892** see Kepler-457

## K2

**K2-1** see WASP-28**K2-2** HIP 116454 in NASA; first discovery by K2, with radial velocity confirmation by HARPS-N, and transit confirmation by MOST (Vanderburg et al., 2015b)>**K2-3** 3-planet system; discovery (Crossfield et al., 2015)> measurement with HARPS (Almenara et al., 2015a)> confirmation from transits (Montet et al., 2015b)> Spitzer observations (Beichman et al., 2016)> radial velocity monitoring with HARPS, PFS, and TRES (Dai et al., 2016)> observations with Okayama 1.88-m and MuSCAT (Fukui et al., 2016a)> multi-planet analysis (Sinukoff et al., 2016)> variable incident flux due to obliquity and eccentricity (Kane & Torres, 2017)>**K2-4** discovery (Montet et al., 2015b)> validation (Crossfield et al., 2016)>**K2-5** 2-planet system; discovery (Montet et al., 2015b)> validation (Crossfield et al., 2016)> multi-planet analysis (Sinukoff et al., 2016)>**K2-6** discovery (Montet et al., 2015b)> validation (Crossfield et al., 2016)>**K2-7** discovery (Montet et al., 2015b)> validation (Crossfield et al., 2016)>**K2-8** 2-planet system; discovery of planet b (Montet et al., 2015b)> validation (Crossfield et al., 2016)> discovery of planet c (Sinukoff et al., 2016)>**K2-9** discovery (Montet et al., 2015b)> validation (Crossfield et al., 2016)> spectra and adaptive optics imaging (Schlieder et al., 2016a)>**K2-10** discovery (Montet et al., 2015b)> validation (Crossfield et al., 2016)> radial velocity follow-up (Van Eylen et al., 2016b)>

- K2-11 ... K2-15** discovery (Montet et al., 2015b)> validation (Crossfield et al., 2016)>
- K2-16** 2-planet system; discovery (Montet et al., 2015b)> validation (Crossfield et al., 2016)> multi-planet analysis (Sinukoff et al., 2016)>
- K2-17** discovery (Montet et al., 2015b)> validation (Crossfield et al., 2016)>
- K2-18** 2-planet system, planet c non-transiting; discovery of planet b (Montet et al., 2015b)> validation (Crossfield et al., 2016)> confirmation and habitable zone from Spitzer observations (Benneke et al., 2017)> radial velocity discovery of non-transiting planet c (Cloutier et al., 2017a)>
- K2-19** 3-planet system; discovery of planets b and c (Montet et al., 2015b)> independent discovery, proximity to 3:2 resonance, and simultaneous transits (Armstrong et al., 2015b)> photo-dynamical mass determination (Barros et al., 2015)> high-dispersion spectroscopy, adaptive optics imaging, and transit timing variations (Narita et al., 2015b)> validation (Crossfield et al., 2016)> radial velocity monitoring with HARPS, PFS, and TRES (Dai et al., 2016)> multi-planet analysis (Sinukoff et al., 2016)> masses of planets b and c from radial velocities and transit timing variations (Nespral et al., 2017)>
- K2-20** see HAT-P-56
- K2-21** 2-planet system; discovery (Petigura et al., 2015)> validation (Crossfield et al., 2016)>
- K2-22** short-period ( $P = 9.1$  h) disintegrating rocky planet; discovery (Sanchis-Ojeda et al., 2015a)> validation (Crossfield et al., 2016)>
- K2-23** see WASP-47
- K2-24** 2-planet system, both low-density sub-Saturn mass; discovery (Petigura et al., 2016)> validation (Crossfield et al., 2016)> radial velocity monitoring with HARPS, PFS, and TRES (Dai et al., 2016)> multi-planet analysis (Sinukoff et al., 2016)>
- K2-25** first transiting planet in the Hyades cluster (Neptune-sized, transiting a M4.5 dwarf); discovery (Mann et al., 2016a)> validation (Crossfield et al., 2016)>
- K2-26** discovery (Schlieder et al., 2016a)> Spitzer observations (Beichman et al., 2016)> validation (Crossfield et al., 2016)>
- K2-27** validation (Crossfield et al., 2016)> radial velocity follow-up (Van Eylen et al., 2016b)> sub-Saturnian mass diversity from Keck-HIRES (Petigura et al., 2017b)>
- K2-28** discovery (Hirano et al., 2016a)> validation (Crossfield et al., 2016)>
- K2-29**  $\equiv$  WASP-152; deep transit (20 mmag), detected by Super-WASP, then by K2; discovery by K2 (Johnson et al., 2016d)> discovery and Rossiter-McLaughlin effect from WASP (Santerne et al., 2016a)>
- K2-30** discovery (Johnson et al., 2016d)> validation (Crossfield et al., 2016)> radial velocities from SOPHIE, HARPS-N and CAFE (Lillo-Box et al., 2016b)> independent discovery (Brahm et al., 2016a)>
- K2-31** first transiting hot Jupiter from K2, with grazing transit; joint discovery (as EPIC-204129699) and radial velocity monitoring with HARPS, PFS, and TRES (Dai et al., 2016)> joint discovery, radial velocity monitoring with FIES and HARPS, and grazing transit (Grziwa et al., 2016)> validation (Crossfield et al., 2016)>
- K2-32** 3-planet system; discovery and radial velocity monitoring with HARPS, PFS, and TRES (Dai et al., 2016)> validation (Crossfield et al., 2016)> multi-planet analysis (Sinukoff et al., 2016)> sub-Saturnian mass diversity from Keck-HIRES (Petigura et al., 2017b)>
- K2-33** in Upper Sco; discovery (David et al., 2016)> validation (Crossfield et al., 2016)> confirmation and characterisation from MEarth (Mann et al., 2016b)> limits on low-frequency radio emission (Lynch et al., 2017)>
- K2-34** discovery, Rossiter-McLaughlin effect, and faint companion candidate (Hirano et al., 2016b)> validation (Crossfield et al., 2016)> radial velocities from SOPHIE, HARPS-N and CAFE (Lillo-Box et al., 2016b)> independent discovery (Brahm et al., 2016a)> recovery from K2SC pipeline processing (Pope et al., 2016)>
- K2-35** 2-planet system; discovery (Sinukoff et al., 2016)> validation (Crossfield et al., 2016)>
- K2-36** 2-planet system; discovery (Sinukoff et al., 2016)> validation (Crossfield et al., 2016)>
- K2-37** 3-planet system discovery (Sinukoff et al., 2016)> validation (Crossfield et al., 2016)>
- K2-38** 2-planet system discovery (Sinukoff et al., 2016)> validation (Crossfield et al., 2016)>
- K2-39** discovery (Van Eylen et al., 2016a)> validation (Crossfield et al., 2016)> sub-Saturnian mass diversity from Keck-HIRES (Petigura et al., 2017b)>
- K2-40** see WASP-75
- K2-41** see WASP-157
- K2-42** validation (Crossfield et al., 2016)>
- K2-43** validation (Crossfield et al., 2016)>
- K2-44** validation (Crossfield et al., 2016)> radial velocity follow-up (Van Eylen et al., 2016b)>
- K2-45 ... K2-55** discovery (Crossfield et al., 2016)> Amongst these:  
K2-51: re-classified as low-mass (binary) star (Shporer et al., 2017b)>
- K2-56** BD+20 594 in NASA; discovery (Espinoza et al., 2016b)>
- K2-57** discovery (Crossfield et al., 2016)>
- K2-58** 3-planet system; discovery (Crossfield et al., 2016)>
- K2-59** 2-planet system; discovery (Crossfield et al., 2016)>
- K2-60** discovery (Crossfield et al., 2016)> independent discovery (Eigmüller et al., 2017)>
- K2-61 ... K2-92** 1-, 2-, 3-, and 4-planet systems (Crossfield et al., 2016)> Amongst these:  
K2-66: mass and density measurements (Sinukoff et al., 2017a)>  
K2-67: re-classified as low-mass (binary) star (Shporer et al., 2017b)>  
K2-76: re-classified as low-mass (binary) star (Shporer et al., 2017b)>  
K2-77: in the Pleiades (Campaign 4) field, but not considered a cluster member (Gaidos et al., 2017b)> K2-78: re-classified as eclipsing binary (Cabrera et al., 2017)>  
K2-82: re-classified as eclipsing binary (Cabrera et al., 2017)>  
K2-92: re-classified as eclipsing binary (Cabrera et al., 2017)>
- K2-93** HIP 41378 in NASA; 5-planet system; discovery (Vanderburg et al., 2016a)>
- K2-94** see WASP-85A
- K2-95** in Praesepe; M-dwarf (JS 183) with Neptune-sized planet; discovery (Obermeier et al., 2016a)> stellar parameters and cluster membership (Mann et al., 2017b)> independent discovery (Pepper et al., 2017a)>
- K2-96** HD 3167 in NASA; 3-planet system, planet d non-transiting; discovery of 2 super-Earths (Vanderburg et al., 2016b)> discovery of planet d from radial velocity, and masses for all 3 planets (Christiansen et al., 2017)> radial velocity follow-up with NOT-FIES and revised parameters (Gandolfi et al., 2017)>
- K2-97** discovery around a red giant (Grunblatt et al., 2016)> revise mass (Grunblatt et al., 2017)>
- K2-98** discovery (Barragán et al., 2016)>
- K2-99** discovery (Smith et al., 2017)>
- K2-100** in Praesepe; discovery, stellar parameters and cluster membership (Mann et al., 2017b)>
- K2-101** in Praesepe; discovery, stellar parameters and cluster membership (Mann et al., 2017b)>
- K2-102** in Praesepe; discovery, stellar parameters and cluster membership (Mann et al., 2017b)>
- K2-103** EPIC-211822797 in NASA; in Praesepe; discovery, stellar parameters and cluster membership (Mann et al., 2017b)>
- K2-104** in Praesepe; discovery, stellar parameters and cluster membership (Mann et al., 2017b)>
- K2-105** discovery (Narita et al., 2017)>
- K2-106** EPIC-220674823 in NASA; 2-planet system, periods 0.57 d and 13.3 d; discovery (Adams et al., 2017)> mass and density measurements (Guenther et al., 2017)> mass and density measurements (Sinukoff et al., 2017a)>
- K2-107** discovery (Eigmüller et al., 2017)>
- K2-108** discovery, and sub-Saturnian mass diversity from Keck-HIRES (Petigura et al., 2017b)>
- K2-109** HD 106315 in NASA; 2-planet system; discovery (Crossfield et al., 2017)> independent discovery (Rodríguez et al., 2017b)> ground-based photometry of planet c with 1.2-m Euler telescope (Lendl et al., 2017b)> improved masses from HARPS radial velocity observations (Barros et al., 2017)> constraints on outer planets on inclined orbits (Read et al., 2017)>
- K2-110** discovery (Osborn et al., 2017b)>
- K2-111** discovery (Fridlund et al., 2017)>
- K2-112** see TRAPPIST-1



- K2-113** discovery (Espinoza et al., 2017b)>  
**K2-114** discovery (Shporer et al., 2017a)>  
**K2-115** discovery (Shporer et al., 2017a)>  
**K2-116 ... K2-130** 1-planet systems except for the 2-planet system K2-117; discovery (Dressing et al., 2017)>  
**K2-131** discovery (Dai et al., 2017a)>  
**K2-132** discovery (Grünblatt et al., 2017)>  
**K2-133** 3-planet system around the M dwarf LP 358-499; discovery (Wells et al., 2018a)>  
**K2-134** see WASP-151  
**K2-135** GJ 9827 in NASA; 3-planet super-Earth system close to a 1:3:5 mean motion resonance; discovery (Niraula et al., 2017)> independent discovery (Rodríguez et al., 2018)>  
**K2-136** 3-planet circumprimary system (Earth, mini-Neptune and super-Earth) orbiting a Hyades cluster K dwarf; discovery (Mann et al., 2018)> independent discovery of planet c (Ciardi et al., 2018)>  
**K2-137** ultra-short period (4.3-h) planet around an M dwarf; discovery (Smith et al., 2018)>  
**K2-138** 5-planet system of sub-Neptune mass, discovered by Citizen Scientists, in an unbroken chain of near 3:2 resonances; discovery (Christiansen et al., 2018)>  
**K2-139** discovery (Barragán et al., 2018)>
- In NASA Exoplanet Archive after 2018-01-01:
- K2-140** discovery (Giles et al., 2018)> ephemeris refinement (Močnik et al., 2018)>  
**K2-141** discovery (Malavolta et al., 2018)>  
**K2-146 ... K2-154** 1-, 2-, and 3-planet systems; (Hirano et al., 2018a)>  
**K2-155** discovery (Hirano et al., 2018b)>  
**K2-156 ... K2-230** 1-, 2-, 3-, and 4-planet systems; (Mayo et al., 2018)>  
**K2-231** sub-Neptune transiting a solar twin in the cluster Ruprecht 147; discovery (Curtis et al., 2018)>

### LHS

- LHS 1140** discovery (Dittmann et al., 2017b)>

### Lupus

- Lupus-TR-3** discovery (Weldrake et al., 2008a)>

### MASCARA

- MASCARA-1** first discovery with MASCARA north (La Palma); hot Jupiter orbiting a  $V = 8.3$  mag A star; discovery and Rossiter-McLaughlin effect (Talens et al., 2017a)>  
**MASCARA-2** see KELT-20

### NGTS

- NGTS-1** short-period high-mass planet ( $P = 2.674$ -d,  $M_p = 0.8M_J$ ) with deep (2.5%) grazing transits around an M-dwarf; discovery (Bayliss et al., 2018a)>

### OGLE

- OGLE-TR-10** identification from spectroscopy (Dreizler et al., 2002)> confirmation from radial velocity (Konacki et al., 2005)> stellar age from Li, Ca II, and rotation (Melo et al., 2006)> stellar parameters from spectroscopy (Santos et al., 2006a)> stellar parameters (Santos et al., 2006b)> additional transits and improved system parameters (Holman et al., 2007a)> planet radius from photometry (Pont et al., 2007b)> homogeneous analysis and light curve properties (Southworth, 2008)> flare during transit, inferred high X-ray luminosity (Bentley et al., 2009)> light curve properties (Southworth, 2009)> light curve properties (Southworth, 2010)>  
**OGLE-TR-56** near-grazing transit; discovery, radial velocity, atmospheric stability (Konacki et al., 2003a)> tidal dissipation, planet migration, atmospheric stability (Sasselov, 2003)> comparison of planet radius with theory (Burrows et al., 2004a)> effect of tidal locking

on magnetospheric and atmospheric evolution (Grießmeier et al., 2004)> tidal dissipation and in-spiraling (Pätzold et al., 2004)> additional radial velocity and OGLE photometry (Torres et al., 2004a)> exclusion of blending (Torres et al., 2005)> simultaneous photometry/radial velocity Wilson-Devinney (binary star) fitting (Vaccaro & Van Hamme, 2005)> stellar age from Li, Ca II, and rotation (Melo et al., 2006)> stellar parameters from spectroscopy (Santos et al., 2006a)> stellar parameters (Santos et al., 2006b)> tidal dissipation and stellar spin-up (Carone & Pätzold, 2007)> mass loss through hydrodynamic escape (Erkaev et al., 2007)> planet radius from photometry (Pont et al., 2007b)> homogeneous analysis and light curve properties (Southworth, 2008)> apsidal precession due to planetary tidal bulge (Ragozzine & Wolf, 2009)> light curve properties (Southworth, 2009)> secondary eclipse from ground photometry (Sing & López-Morales, 2009)> homogeneous analysis and light curve properties (Southworth, 2010)> 19 transits between 2003-09 (Adams et al., 2011a)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> tidal effects on radial velocity (Arras et al., 2012)> photometry and new spectroscopy (Southworth, 2012)>

**OGLE-TR-111** discovery, radial velocity (Pont et al., 2004)> stellar age from Li, Ca II, and rotation (Melo et al., 2006)> stellar parameters from spectroscopy (Santos et al., 2006a)> stellar parameters (Santos et al., 2006b)> ground photometry (Minniti et al., 2007)> two additional transits (Winn et al., 2007b)> transit time variations (Díaz et al., 2008)> homogeneous analysis and light curve properties (Southworth, 2008)> light curve properties (Southworth, 2009)> transit time variations questioned (Adams et al., 2010a)> light curve properties (Southworth, 2010)> five new transits from ESO-FORS, dynamical modeling (Hoyer et al., 2011)> photometry and new spectroscopy (Southworth, 2012)>

**OGLE-TR-113** discovery, radial velocity (Bouchy et al., 2004)> independent confirmation from radial velocity (Konacki et al., 2004)> tidal dissipation (Pätzold et al., 2004)> transit light curves (Gillon et al., 2006)> stellar age from Li, Ca II, and rotation (Melo et al., 2006)> stellar parameters from spectroscopy (Santos et al., 2006a)> stellar parameters (Santos et al., 2006b)> additional transits and improved parameters (Díaz et al., 2007)> infrared transits and possible secondary eclipse from NTT-SOFI (Snellen & Covino, 2007)> additional transits 2007-09 and limits on transit time variations (Adams et al., 2010b)> homogeneous analysis and light curve properties (Southworth, 2010)> photometry and new spectroscopy (Southworth, 2012)> transits negate rapid orbital decay (Hoyer et al., 2016a)> dynamical tides excited by gravity waves in host star affecting planet's orbital evolution (Chernov et al., 2017)>

**OGLE-TR-132** discovery, radial velocity (Bouchy et al., 2004)> improved photometry and system parameters (Moutou et al., 2004)> tidal dissipation (Pätzold et al., 2004)> stellar abundances from spectroscopy (Santos et al., 2006a)> improved photometry (Gillon et al., 2007c)> homogeneous analysis and light curve properties (Southworth, 2008)> light curve properties (Southworth, 2009)> light curve properties (Southworth, 2010)> seven new transits, limits on transit time variations (Adams et al., 2011b)> photometry and new spectroscopy (Southworth, 2012)>

**OGLE-TR-182** discovery, radial velocity (Pont et al., 2008b)> homogeneous analysis and light curve (Southworth, 2010)>

**OGLE-TR-211** discovery, radial velocity (Udalski et al., 2008)> homogeneous analysis and light curve (Southworth, 2010)>

**OGLE2-TR-L9** discovery, radial velocity (Snellen et al., 2009b)> 5 transits and possible transit time variations (Lendl et al., 2010)> homogeneous analysis and light curve properties (Southworth, 2010)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> tidal effects on radial velocity (Arras et al., 2012)> photometry and spectroscopy (Southworth, 2012)>

### PH

**PH-1** see Kepler-64

**PH-2** see Kepler-86

### POTS

**POTS-1** discovery from Pre-OmegaCam Transit Survey (Koppenhoefer et al., 2013)>

## PTFO

**PTFO 8-8695**  $\equiv$  CVSO 30; planet(s) are not confirmed, and not in NASA archive; claimed orbital periods are 0.45 d and 27 000 yr, suggestive of formation by planet–planet scattering; transit profiles are of unusual shape, and variable; young hot Jupiter candidate,  $M_p \sim 3M_J$ ,  $P = 0.45$  d, around a T Tauri star; discovery (van Eyken et al., 2012)  $\triangleright$  spin–orbit misalignment and nodal precession (Barnes et al., 2013a)  $\triangleright$  planet not confirmed (Ciardi et al., 2015b)  $\triangleright$  precession period of 199 d from photometry for a non-spin–orbit synchronous orbit (Kamiaka et al., 2015)  $\triangleright$  photometric variability described by rotating star spots (Koen, 2015)  $\triangleright$  tests of planetary hypothesis (Yu et al., 2015)  $\triangleright$  reappraisal of planet parameters (Howarth, 2016)  $\triangleright$  variable H $\alpha$  emission favours planet interpretation (Johns-Krull et al., 2016b)  $\triangleright$  33 fading events from 144 nights observations over three years (Raetz et al., 2016)  $\triangleright$  imaging discovery of second planet candidate at 1.85 arcsec or 660 au (Schmidt et al., 2016)  $\triangleright$  Roche lobe overflow model and mass-loss for short-period gaseous planets (Jackson et al., 2017b)  $\triangleright$  3-colour photometry favours circumstellar dust clump or occultation of accretion hotspot (Onitsuka et al., 2017)  $\triangleright$  evidence that planet c is a background star (Lee & Chiang, 2018)  $\triangleright$

## Qatar

**Qatar-1** discovery, radial velocity (Alsubai et al., 2011)  $\triangleright$  Rossiter–McLaughlin effect, revised system parameters (Covino et al., 2013)  $\triangleright$  transit time variations from OLT and PTST (von Essen et al., 2013)  $\triangleright$  chromospheric activity (Kuznyetsova et al., 2014)  $\triangleright$  secondary eclipse with CFHT-WIRCam and limits on ground-based systematics (Croll et al., 2015a)  $\triangleright$  no variation in transit times (Maciejewski et al., 2015)  $\triangleright$  high-precision multicolour time series photometry (Mislis et al., 2015)  $\triangleright$  secondary eclipse in the Ks band with Calar Alto-OMEGA2000 (Cruz et al., 2016)  $\triangleright$  limits on transit timing variations (Collins et al., 2017a)  $\triangleright$  photometry and transit times (Püsküllü et al., 2017)  $\triangleright$  ground-based transmission spectrum with GEMINI-N-GMOS (von Essen et al., 2017)  $\triangleright$  Spitzer secondary eclipses (Garhart et al., 2018)  $\triangleright$

**Qatar-2** discovery, radial velocity, evidence of second planet in outer orbit (Bryan et al., 2012)  $\triangleright$  17 light curves of five transits with obliquity from star spots (Mancini et al., 2014c)  $\triangleright$  gyrochronology and isochrone ages (Maxted et al., 2015b)  $\triangleright$  recovery from K2SC pipeline processing (Pope et al., 2016)  $\triangleright$  orbital obliquity, planet mass, and very low albedo from K2 photometry (Dai et al., 2017b)  $\triangleright$  Rossiter–McLaughlin effect and orbital obliquity from HARPS-N (Esposito et al., 2017)  $\triangleright$  recurring sets of recurring star spot occultations (Močnik et al., 2017c)  $\triangleright$

**Qatar-3** discovery, radial velocity (Alsubai et al., 2017)  $\triangleright$

**Qatar-4** discovery, radial velocity (Alsubai et al., 2017)  $\triangleright$

**Qatar-5** discovery, radial velocity (Alsubai et al., 2017)  $\triangleright$

**Qatar-6** grazing transit orbiting a bright  $V = 11.4$  K dwarf with  $P = 3.5$  d; discovery (Alsubai et al., 2018)  $\triangleright$

## SWEEPS

**SWEEPS-4** identification and confirmation from radial velocity (Sahu et al., 2006)  $\triangleright$

**SWEEPS-11** identification and confirmation from radial velocity (Sahu et al., 2006)  $\triangleright$  tidal effects on radial velocity (Arras et al., 2012)  $\triangleright$

## TRAPPIST

**TRAPPIST-1**  $\equiv$  K2-112; 7-planet system around an ultracool ( $T < 2700$  K) dwarf star at 12 pc, all of terrestrial mass, orbiting within the (habitable zone) orbital radius of Mercury, and with three-body resonances linking each planet; discovery of 3-planet system with TRAPPIST (Gillon et al., 2016)  $\triangleright$  prospects for detection of O $_3$  with JWST (Barstow & Irwin, 2016)  $\triangleright$  prospects for detection of Rossiter–McLaughlin effect (Cloutier & Triard, 2016)  $\triangleright$  combined HST transmission of planets b and c excludes cloud-free H $_2$ -atmosphere (de Wit et al., 2016b)  $\triangleright$  recovery prospects with K2 (Demory et al., 2016c)  $\triangleright$  speckle imaging excludes low-mass companions (Howell et al., 2016b)  $\triangleright$  climate–vegetation energy-balance habitability model (Alberti et al., 2017)  $\triangleright$  updated astrometry and photometric variability over 12 years (Bartlett et al., 2017)  $\triangleright$  H $_2$ O loss during the hot early phase of stellar cooling (Bolmont et al., 2017b)  $\triangleright$  trigonometric

distance and mass constraints (Boss et al., 2017)  $\triangleright$  H $_2$ O loss during the hot early phase of stellar cooling (Bourrier et al., 2017b)  $\triangleright$  system Ly- $\alpha$  emission from HST-STIS (Bourrier et al., 2017e)  $\triangleright$  biased transit depths from overlapping stellar and planetary lines (Deming & Sheppard, 2017)  $\triangleright$  stellar wind, and magnetic and plasma environment (Garraffo et al., 2017)  $\triangleright$  discovery of four further planets with TRAPPIST (Gillon et al., 2017c)  $\triangleright$  probable absence of exomoons (Kane, 2017)  $\triangleright$  litho-panspermia  $10^4 - 10^5$  faster than solar system (Krijt et al., 2017)  $\triangleright$  litho-panspermia propagation and observational metrics (Lingam & Loeb, 2017a)  $\triangleright$  reduced diversity of life around M dwarfs from atmospheric erosion (Lingam & Loeb, 2017c)  $\triangleright$  K2 observations constrain orbit for planet h, and confirm 7-planet resonant chain (Luger et al., 2017c)  $\triangleright$  planet–planet occultations outside of transit observable with JWST (Luger et al., 2017a)  $\triangleright$  suitability for JWST (Morley et al., 2017b)  $\triangleright$  ultraviolet surface environment models and habitability (O’Malley-James & Kaltenegger, 2017)  $\triangleright$  formation through pebble-accretion at the H $_2$ O-ice line (Ormel et al., 2017)  $\triangleright$  Earth-like compositions confirmed from N-body simulations (Quares et al., 2017)  $\triangleright$  stellar activity and likely ultraviolet atmospheric erosion (Roettenbacher & Kane, 2017)  $\triangleright$  system longevity as a result of convergent migration (Tamayo et al., 2017)  $\triangleright$  eclipse, transit and occultation geometry at exo-syzygy (Veras & Breed, 2017)  $\triangleright$  stellar flaring from K2 observations and implications for habitability (Vida et al., 2017)  $\triangleright$  XMM-Newton X-ray observations and high  $L_X/L_{\text{bol}}$  (Wheatley et al., 2017)  $\triangleright$  habitability from 3d climate models (Wolf, 2017)  $\triangleright$  as an example of anti-correlation between multiplicity and eccentricity (Zinzi & Turrini, 2017)  $\triangleright$  stratospheric circulation and O $_3$  production in tidally locked planets (Carone et al., 2018)  $\triangleright$  refined transit parameters from Spitzer-IRAC and limits on stellar variability (Delrez et al., 2018a)  $\triangleright$  atmospheric reconnaissance of the habitable zone planet (de Wit et al., 2018)  $\triangleright$  atmospheric escape and habitability (Dong et al., 2018)  $\triangleright$  planet masses and densities from transit timing variations (Grimm et al., 2018)  $\triangleright$  spin–orbital tidal dynamics and tidal heating (Makarov et al., 2018)  $\triangleright$  possible bright star spots (Morris et al., 2018a)  $\triangleright$  photometric analysis and transit times of planets b and c (Morris et al., 2018b)  $\triangleright$  re-analysis of HST-WFC3 near-infrared transmission spectra (Zhang et al., 2018b)  $\triangleright$

## TrES

**TrES-1** discovery, radial velocity (Alonso et al., 2004)  $\triangleright$  spectroscopic determination of stellar parameters, chemical abundances, age (Sozzetti et al., 2004)  $\triangleright$  secondary eclipses and atmospheric modeling from Spitzer (Burrows et al., 2005)  $\triangleright$  detection of thermal emission with Spitzer (Charbonneau et al., 2005)  $\triangleright$  secondary eclipses and atmospheric modeling from Spitzer (Fortney et al., 2005)  $\triangleright$  humps in AAVSO egress (Price et al., 2005)  $\triangleright$  limits on transit time variations (Steffen & Agol, 2005)  $\triangleright$  stellar age from Li, Ca II, and rotation (Melo et al., 2006)  $\triangleright$  stellar parameters and abundances from spectroscopy (Santos et al., 2006a)  $\triangleright$  stellar parameters (Santos et al., 2006b)  $\triangleright$  stellar parameters (Sozzetti et al., 2006c)  $\triangleright$  mass loss through hydrodynamic escape (Erkaev et al., 2007)  $\triangleright$  limits on secondary eclipse from ground (Knutson et al., 2007b)  $\triangleright$  Rossiter–McLaughlin effect (Narita et al., 2007)  $\triangleright$  improved photometry and absence of star spots (Winn et al., 2007d)  $\triangleright$  homogeneous analysis and light curve properties (Southworth, 2008)  $\triangleright$  possible star spots (Dittmann et al., 2009b)  $\triangleright$  star spots or second transiting planet from HST photometry (Rabus et al., 2009a)  $\triangleright$  limits on transit time variations (Rabus et al., 2009c)  $\triangleright$  additional transits (Raetz et al., 2009b)  $\triangleright$  light curve properties (Southworth, 2009)  $\triangleright$  homogeneous analysis and light curve properties (Southworth, 2010)  $\triangleright$  transits observed with Shandong/Weihai 1-m (Zhang et al., 2011)  $\triangleright$  stellar companion from lucky imaging (Faedi et al., 2013b)  $\triangleright$  reanalysis of Spitzer transits and eclipses (Cubillos et al., 2014)  $\triangleright$  compilation of light curves and transit timing (Baluev et al., 2015)  $\triangleright$

**TrES-2**  $\equiv$  Kepler-1; discovered in pre-operational Kepler field; near-grazing transit, very low albedo; discovery, radial velocity (O’Donovan et al., 2006a)  $\triangleright$  additional transits and improved system parameters (Holman et al., 2007b)  $\triangleright$  additional transits and improved system parameters (Sozzetti et al., 2007)  $\triangleright$  homogeneous analysis and light curve properties (Southworth, 2008)  $\triangleright$  Rossiter–McLaughlin effect (Winn et al., 2008e)  $\triangleright$  stellar binary (Daemgen et al., 2009)  $\triangleright$  orbit stability (Freistetter et al., 2009)  $\triangleright$  change in transit duration due to change in orbit inclination (Mislis & Schmitt, 2009)  $\triangleright$  limits on transit time variations (Rabus et al., 2009c)  $\triangleright$  additional transits (Raetz et al., 2009a)  $\triangleright$  light curve properties (Southworth, 2009)  $\triangleright$

- transit observations with GTC (Colón et al., 2010)> secondary eclipse from CFHT (Croll et al., 2010a)> effects of data binning (Kipping, 2010a)> additional transits (Mislis et al., 2010b)> thermal inversion and molecular abundances (Madhusudhan & Seager, 2010)> secondary eclipses from Spitzer (O'Donovan et al., 2010)> limits on changes in orbit inclination (Scuderi et al., 2010)> atmospheric models from Spitzer and Kepler (Spiegel & Burrows, 2010)> homogeneous analysis and light curve properties (Southworth, 2010)> search for additional planets from EPOXI (Ballard et al., 2011a)> possible star spots from EPOXI (Christiansen et al., 2011)> 18 transits from Kepler, system parameters, limits on albedo (Kipping & Bakos, 2011b)> limits on transit time variations and albedo (Kipping & Spiegel, 2011)> photometry and new spectroscopy (Southworth, 2011)> 2.7-yr of Kepler data, asteroseismology, ellipsoidal variations, Doppler beaming, albedo, secondary eclipse, and atmospheric constraints (Barclay et al., 2012)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> possible change in orbit inclination (Schröter et al., 2012)> modeling from 15 quarters of Kepler (Esteves et al., 2013)> confirmed stellar companion from lucky imaging (Faedi et al., 2013b)> atmospheric disequilibrium diagnostics (Line & Yung, 2013)> atmospheric disequilibrium diagnostics (Line et al., 2014)> transit times from 490 transits (Raetz et al., 2014)> atmospheric characterisation with HST-WFC3 (Ranjan et al., 2014)> Kepler secondary eclipse and phase curves (Angerhausen et al., 2015a)> Kepler phase curve with beaming and ellipsoidal variations (Esteves et al., 2015)> Kepler phase curves with beaming, ellipsoidal, and reflection phase modulation (Faigler & Mazeh, 2015)> nearby star from lucky imaging (Wöllert et al., 2015)> photometric analysis of all Kepler data (Budding et al., 2016b)> use as a precision clock to constrain time variation of the gravitational constant (Masuda & Suto, 2016)> no asymmetry in ground-based ultraviolet transits (Turner et al., 2016b)> heat recirculation and albedo from comparison of optical phase curve and secondary eclipse (von Paris et al., 2016b)> simple transit model (Ji et al., 2017)> climate models (Wang & Cuntz, 2017)>
- TRES-3** discovery, radial velocity confirmation (O'Donovan et al., 2007)> limits on secondary eclipse (Winn et al., 2008c)> secondary eclipse from WHT/UKIRT (de Mooij & Snellen, 2009)> 9 transits from RISE, limits on transit time variations (Gibson et al., 2009)> apsidal precession due to planetary tidal bulge (Ragozzine & Wolf, 2009)> photometry, spectroscopy, and revised system parameters (Sozzetti et al., 2009a)> transit observations with GTC (Colón et al., 2010)> secondary eclipse in Ks from CFHT (Croll et al., 2010b)> broadband infrared emission spectrum (Fressin et al., 2010)> homogeneous analysis and light curve properties (Southworth, 2010)> search for additional planets from EPOXI (Ballard et al., 2011a)> 7 transits from EPOXI, possible star spots (Christiansen et al., 2011)> polarisation studies (Kostogryz et al., 2011)> ephemeris from 109 transits, possible star spots (Lee et al., 2011c)> photometry and new spectroscopy (Southworth, 2011)> prospects for detecting bow shocks (Vidotto et al., 2011a)> transits observed with Shandong/Weihai 1-m (Zhang et al., 2011)> possible transit time variations from 23 light curves (Jiang et al., 2013a)> transits from Apache Point-APOSTLE (Kundurthy et al., 2013b)> atmospheric disequilibrium diagnostics (Line & Yung, 2013)> transit times from 2009-2013 consistent with linear ephemeris (Maciejewski et al., 2013c)> constraints on magnetic field from near ultraviolet transits (Turner et al., 2013)> no transit time variations (Vaňko et al., 2013)> atmospheric disequilibrium diagnostics (Line et al., 2014)> atmospheric characterisation with HST-WFC3 (Ranjan et al., 2014)> Rayleigh scattering from GTC-OSIRIS (Parvainen et al., 2016)> improved orbit from HARPS-N (Bonomo et al., 2017a)> improved spectroscopy favours a flat spectrum (Mackebrandt et al., 2017)> photometry and transit times (Püsküllü et al., 2017)> linear ephemeris over 9 yr (Ricci et al., 2017a)> improved ground-based transit photometry using beam-shaping diffusers (Steffansson et al., 2017)> photometric follow-up and transit timing analysis with the Xuyi Near-Earth Object Survey Telescope (Zhao et al., 2018b)>
- TRES-4** hot Jupiter with large radius ( $1.8R_J$ )> discovery, radial velocity (Mandushev et al., 2007)> modeling of radius (Liu et al., 2008a)> stellar binary (Daemgen et al., 2009)> secondary eclipses and atmospheric temperature inversion from Spitzer (Knutson et al., 2009a)> photometry, spectroscopy, and revised system parameters (Sozzetti et al., 2009a)> inflation through Ohmic dissipation (Batygin & Stevenson, 2010)> tidal heating (Ibgui et al., 2010)> thermal inversion and molecular abundances (Madhusudhan & Seager, 2010)>
- Rossiter-McLaughlin effect and additional radial velocity variability (Narita et al., 2010c)> homogeneous analysis and light curve properties (Southworth, 2010)> transits and improved ephemeris (Chan et al., 2011)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> coupled radius-orbit evolutionary models (Ibgui et al., 2011)> new transits confirming large radius (Chan et al., 2012)> photometry and new spectroscopy (Southworth, 2012)> lucky imaging confirmation of common proper motion companion (Bergfors et al., 2013)> confirmed stellar companion from lucky imaging (Faedi et al., 2013b)> atmospheric characterisation with HST-WFC3 (Ranjan et al., 2014)> significantly lower mass from HARPS-N, and very low density (Sozzetti et al., 2015)> nearby star from lucky imaging (Wöllert et al., 2015)> no asymmetry in ground-based ultraviolet transits (Turner et al., 2016b)>
- TRES-5** discovery, radial velocity (Mandushev et al., 2011)> high-precision multicolour time series photometry (Mislis et al., 2015)> photometry with a DSLR camera (Miller, 2015)> additional transit observations (Maciejewski et al., 2016b)>

## WASP

**ISWASP J1407** (ISWASP J140747.93-394542.6); not in NASA; although not attributed directly to a planet, the star shows long, deep, eclipses, modeled as a system of circumstellar or circumplanetary disks; discovery of the transiting ring system (Mamajek et al., 2012)> eclipse fine-structure and hints of exomoons (van Werkhoven et al., 2014b)> ring possibly sculpting by exomoons (Kenworthy & Mamajek, 2015b)> mass and period limits on the ringed companion (Kenworthy et al., 2015)> constraints on size/dynamics (Rieder & Kenworthy, 2016)> constraints on disks/rings (Zanazzi & Lai, 2017a)>

**WASP-1** discovery, radial velocity (Collier Cameron et al., 2007a)> photometry and planet radius (Charbonneau et al., 2007a)> two transits (Shporer et al., 2007)> stellar spectroscopy, Li abundance, age (Stempels et al., 2007)> homogeneous analysis and light curve properties (Southworth, 2008)> light curve properties (Southworth, 2009)> light curve properties (Southworth, 2010)> limits on Rossiter-McLaughlin effect from Magellan, Subaru, Keck (Albrecht et al., 2011b)> mass loss rate from extreme ultraviolet and X-ray radiation (Ehrenreich & Désert, 2011)> Rossiter-McLaughlin effect from OHP-SOPHIE (Simpson et al., 2011c)> transits observed with Shandong/Weihai 1-m (Zhang et al., 2011)> Rossiter-McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> tidal effects on radial velocity (Arras et al., 2012)> photometry and new spectroscopy (Southworth, 2012)> new transits from Asiago-TASTE, linear ephemeris (Granata et al., 2014)> 13 new transits, revised parameters, linear ephemeris (Maciejewski et al., 2014b)> no asymmetry in ground-based ultraviolet transits (Turner et al., 2016b)>

**WASP-2** discovery, radial velocity (Collier Cameron et al., 2007a)> improved photometry and planet radius (Charbonneau et al., 2007a)> homogeneous analysis and light curve properties (Southworth, 2008)> stellar binary (Daemgen et al., 2009)> light curve properties (Southworth, 2009)> three transits and atmospheric modeling (Southworth et al., 2010)> homogeneous analysis and light curve properties (Southworth, 2010)> Rossiter-McLaughlin effect from ESO-HARPS and CORALIE (Triaud et al., 2010)> limits on Rossiter-McLaughlin effect from Magellan, Subaru, Keck (Albrecht et al., 2011b)> transits observed with Shandong/Weihai 1-m (Zhang et al., 2011)> Rossiter-McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> photometry and new spectroscopy (Southworth, 2012)> lucky imaging confirmation of stellar companion (Bergfors et al., 2013)> transits from Apache Point-APOSTLE and limits on transit time variations (Becker et al., 2013)> compilation of light curves and transit timing (Baluev et al., 2015)> nearby star from lucky imaging (Wöllert et al., 2015)> Ks-band secondary eclipse observations with AAT-IRIS2 (Zhou et al., 2015b)> photometry and atmospheric models (Turner et al., 2017)>

**WASP-3** discovery, radial velocity (Pollacco et al., 2008)> 9 transits from RISE and improved ephemeris (Gibson et al., 2008)> line-profile tomography (Miller et al., 2010)> sinusoidal transit time variations (Maciejewski et al., 2010)> homogeneous analysis and light curve properties (Southworth, 2010)> Rossiter-McLaughlin effect (Simpson et al., 2010b)> Rossiter-McLaughlin effect (Tripathi et al., 2010)> search for additional planets from EPOXI (Ballard et al., 2011a)> 8 transits from EPOXI and limits on secondary eclipse (Christiansen

- et al., 2011)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> sinusoidal transit time variations (Littlefield, 2011)> photometry and new spectroscopy (Southworth, 2011)> transits observed with Shandong/Weihai 1-m (Zhang et al., 2011)> tidal effects on radial velocity (Arras et al., 2012)> possible transit duration variations (Eibe et al., 2012)> new transits and limits on transit time variations (Montalto et al., 2012)> secondary eclipse in Ks from Palomar-WIRC (Zhao et al., 2012b)> 17 radial velocity measurements and 32 transit light curves confirm linear ephemeris (Maciejewski et al., 2013b)> new transits and limits on transit time variations (Nascimbeni et al., 2013a)> 11 new transits, and homogeneous treatment of a further 38, confirm linear ephemeris (Nascimbeni et al., 2013a)> modelling of light curve and radial velocity of transits and spots using SOAP-T (Oshagh et al., 2013a)> rapid atmospheric heat redistribution from Spitzer (Rostron et al., 2014)> secondary eclipse with CFHT-WIRCam and limits on ground-based systematics (Croll et al., 2015a)>
- WASP-4** discovery, radial velocity (Wilson et al., 2008a)> radial velocities and improved parameters (Gillon et al., 2009c)> apsidal precession due to planetary tidal bulge (Ragozzine & Wolf, 2009)> four transits from defocused observations (Southworth et al., 2009a)> two transits and limits on transit time variations (Winn et al., 2009a)> tidal heating models (Ibgui et al., 2010)> homogeneous analysis and light curve properties (Southworth, 2010)> Rossiter-McLaughlin effect (Triaud et al., 2010)> secondary eclipse and atmosphere modeling from Spitzer (Beerer et al., 2011)> secondary eclipse from ground near-infrared photometry (Cáceres et al., 2011)> TERMS photometry (Dragomir et al., 2011)> coupled radius-orbit evolutionary models (Ibgui et al., 2011)> polarisation studies (Kostogryz et al., 2011)> star spots and constraints on spin-orbit alignment (Sanchis-Ojeda et al., 2011)> prospects for detecting bow shocks (Vidotto et al., 2011a)> tidal effects on radial velocity (Arras et al., 2012)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> three transits and limits on transit time variations (Nikolov et al., 2012)> photometry and new spectroscopy (Southworth, 2012)> 12 transits from TraMoS confirm linear ephemeris, star spots give 34 d rotation (Hoyer et al., 2013)> 6 transits and 28 archival confirm linear ephemeris (Petrucci et al., 2013)> atmospheric characterisation with HST-WFC3 (Ranjan et al., 2014)> thermal emission versus orbit phase with HST indicate large day/night variations (Stevenson et al., 2014d)> orbital decay driven by tidal dissipation (Valsecchi & Rasio, 2014a)> compilation of light curves and transit timing (Baluev et al., 2015)> transits with a 0.4-m telescope (Kjurkchieva et al., 2015)> gyrochronology and isochrone ages (Maxted et al., 2015b)> Ks-band secondary eclipse observations with AAT-IRIS2 (Zhou et al., 2015b)> Gemini-GMOS transmission spectrum 440-940 nm (Huitson et al., 2017)>
- WASP-5** discovery, radial velocity (Anderson et al., 2008)> radial velocities and improved parameters (Gillon et al., 2009c)> two transits from defocused observations (Southworth et al., 2009c)> homogeneous analysis and light curve properties (Southworth, 2010)> Rossiter-McLaughlin effect (Triaud et al., 2010)> TERMS photometry (Dragomir et al., 2011)> 7 transits and possible transit time variations (Fukui et al., 2011)> prospects for detecting bow shocks (Vidotto et al., 2011a)> 9 transits with TraMoS confirm linear ephemeris (Hoyer et al., 2012)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> photometry and new spectroscopy (Southworth, 2012)> atmospheric pressure-temperature profile from secondary eclipse with Spitzer-IRAC (Baskin et al., 2013)> secondary eclipse from MPG-GROND (Chen et al., 2014b)> compilation of light curves and transit timing (Baluev et al., 2015)> gyrochronology and isochrone ages (Maxted et al., 2015b)> Ks-band secondary eclipse observations with AAT-IRIS2 (Zhou et al., 2015b)> multicolour characterisation (Moyano et al., 2017)>
- WASP-6** discovery, radial velocity, and Rossiter-McLaughlin effect (Gillon et al., 2009a)> tidal heating (Ibgui et al., 2010)> TERMS photometry (Dragomir et al., 2011)> coupled radius-orbit evolutionary models (Ibgui et al., 2011)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> featureless ground transmission spectrum from Baade-IMACS (Jordán et al., 2013)> Spitzer secondary eclipse observations at 3.6 and 4.5  $\mu\text{m}$  (Kammer et al., 2015)> atmospheric haze (Nikolov et al., 2015)> H<sub>2</sub>O in clear/cloudy atmospheres from infrared transit spectroscopy (Sing et al., 2016)> transits and star spots (Tregloan-Reed et al., 2015)> atmospheric circulation (Kataria et al., 2016)> atmospheric retrieval analysis with NEMESIS (Barstow et al., 2017)>
- WASP-7** discovery, radial velocity (Hellier et al., 2009b)> transit from defocused observations, revised radius (Southworth et al., 2011)> photometry and new spectroscopy (Southworth, 2011)> Rossiter-McLaughlin effect and stellar jitter (Albrecht et al., 2012a)> tidal effects and spin-orbit alignment from eccentricity (Husnoo et al., 2012)> physical properties (Southworth, 2012)>
- WASP-8** 2-planet system, planet b discovered from transits, planet c from radial velocity; discovery of planet b, radial velocity, Rossiter-McLaughlin effect and retrograde orbit (Queloz et al., 2010)> 6 secondary eclipses and atmosphere modeling from Spitzer (Cubillos et al., 2013)> discovery/confirmation of planet c from radial velocity with Keck-HIRES (Knutson et al., 2014c)> Rossiter-McLaughlin effect and refined architecture (Bourrier et al., 2017a)> atmospheric modeling with HELIOS (Malik et al., 2017)>
- WASP-9** unpublished (false positive)
- WASP-10** discovery, radial velocity (Christian et al., 2009)> transits and revised radius (Johnson et al., 2009c)> transits and revised radius (Dittmann et al., 2010)> transits and revised radius (Krejčová et al., 2010)> homogeneous analysis and light curve properties (Southworth, 2010)> transits, star spots, transit time variations (Maciejewski et al., 2011a)> transits, star spots, transit time variations (Maciejewski et al., 2011c)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> transits, star spots, transit time variations (Barros et al., 2013)> radial velocity search for massive long-period companion (Knutson et al., 2014c)> secondary eclipse in the Ks band with Calar Alto-OMEGA2000 (Cruz et al., 2015)> Spitzer secondary eclipse observations at 3.6 and 4.5  $\mu\text{m}$  (Kammer et al., 2015)> gyrochronology and isochrone ages (Maxted et al., 2015b)> transits from Monterrey observatory (Sada & Ramón-Fox, 2016)>
- WASP-11**  $\equiv$  HAT-P-10; discovery, radial velocity (West et al., 2009b)> independently as HAT-P-10 (Bakos et al., 2009c)> infrared transits, star spots (Sada et al., 2012)> radial velocity search for massive long-period companion (Knutson et al., 2014c)> transits from Yunnan confirm linear ephemeris (Wang et al., 2014e)> Rossiter-McLaughlin effect (Mancini et al., 2015a)>
- WASP-12** short period ( $P = 1.09$  d,  $a = 0.2$  au), orbits primary of hierarchical triple system, irradiated and inflated, with early ultraviolet ingress due to bow shocks or Roche lobe overflow; discovery, radial velocity (Hebb et al., 2009)> apsidal precession due to planetary tidal bulge (Ragozzine & Wolf, 2009)> ultraviolet secondary eclipse, exospheric metal absorption, and early ultraviolet ingress from HST (Fossati et al., 2010b)> stellar abundances, limits on stellar magnetic field (Fossati et al., 2010a)> tidal heating (Ibgui et al., 2010)> early ultraviolet transit ingress due to bow shock and Roche lobe overflow/disk accretion (Lai et al., 2010)> mass loss, possible perturbing planet (Li et al., 2010b)> secondary eclipse and atmospheric modeling (López-Morales et al., 2010)> early transit ingress due to bow shock (Vidotto et al., 2010)> reflection effect (Budaj, 2011)> secondary eclipse in near infrared from CFHT-WIRCam (Croll et al., 2011b)> additional transits (Chan et al., 2011)> secondary eclipses and limits on eccentricity and apsidal precession from Spitzer (Campo et al., 2011)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> high mass loss from extreme ultraviolet and X-ray radiation (Ehrenreich & Désert, 2011)> limits on eccentricity from radial velocities (Husnoo et al., 2011)> bow shock (Llama et al., 2011)> transit time variations and possible perturbing planet (Maciejewski et al., 2011b)> CO, H<sub>2</sub>O, and CH<sub>4</sub> abundances (Madhusudhan et al., 2011b)> models of C-rich atmospheric chemistry, thermal inversions, and formation (Madhusudhan et al., 2011c)> C/O ratio arising from effects of the snow line (Öberg et al., 2011)> consideration of bow shocks (Vidotto et al., 2011a)> tidal effects on radial velocity (Arras et al., 2012)> Rossiter-McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> transits, improved ephemeris (Chan et al., 2012)> secondary eclipse and atmospheric modeling from IRTF (Crossfield et al., 2012b)> ellipsoidal variations at 3.6 and 4.5  $\mu\text{m}$  (Cowan et al., 2012b)> narrow-band secondary eclipse photometry and atmospheric modeling (Crossfield et al., 2012a)> wavelength-dependent astrometric motion (Coughlin & López-Morales, 2012b)> near-ultraviolet absorption, chromospheric activity, star-planet interactions (Haswell et al., 2012)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> C<sub>2</sub>H<sub>2</sub> versus CH<sub>4</sub> abundances (Kopparapu et al., 2012)> C/O ratio as a characterisation of atmospheres (Madhusudhan, 2012)> photometry and new

- spectroscopy (Southworth, 2012)> possible star spots or satellites from Pulkovo (Sokov et al., 2012)> Ks-band secondary eclipse from ground (Zhao et al., 2012c)> plasma interactions between planet and host star (Bisikalo et al., 2013)> stellar companion from lucky imaging (Bergfors et al., 2013)> Rayleigh scattering from high-altitude haze from WHT-ULTRACAM (Copperwheat et al., 2013)> absorbing gas from stellar irradiation responsible for low stellar activity index (Fossati et al., 2013a)> C-rich atmosphere from WHT-ULTRACAM (Föhring et al., 2013)> atmospheric disequilibrium diagnostics (Line & Yung, 2013)> 61 transits with transit time variations and possible perturbing planet (Maciejewski et al., 2013a)> C/O modeling and confirmation of C-rich atmosphere (Moses et al., 2013c)> H<sub>2</sub>O absorption at 1.4  $\mu$ m from HST-WFC3 (Mandell et al., 2013)> atmospheric heat redistribution efficiency drops as stellar insolation rises (Perez-Becker & Showman, 2013)> spectroscopy from HST, identification of hot spot near substellar point (Swain et al., 2013)> CO constraints from HST-WFC3 (Swain et al., 2013)> aerosols and lack of TiO from HST-WFC3 (Sing et al., 2013)> C-rich planet formation in a solar-composition disk (Ali-Dib et al., 2014a)> planet orbits primary of hierarchical triple system from Keck imaging (Bechter et al., 2014)> detecting exomoons via a transiting plasma torus (Ben-Jaffel & Ballester, 2014)> atmospheric disequilibrium diagnostics (Line et al., 2014)> orbit parameters versus atmospheric species (Miguel & Kaltenecker, 2014)> H<sub>2</sub>O from HST-WFC3 (Madhusudhan et al., 2014b)> exclusion of cloud-free H<sub>2</sub> atmosphere from Gemini-GMOS (Stevenson et al., 2014c)> C-rich atmosphere from HST and Spitzer secondary eclipses (Stevenson et al., 2014b)> defocused transmission spectroscopy, and possible detection of Na (Burton et al., 2015a)> maximum size of stationary quasi-closed gaseous envelope (Bisikalo et al., 2015)> secondary eclipse with CFHT-WIRCam and limits on ground-based systematics (Croll et al., 2015a)> detection of H<sub>2</sub>O with HST-WFC3 (Kreidberg et al., 2015)> impact of stellar activity on X-ray and ultraviolet transits (Llama & Shkolnik, 2015)> near ultraviolet transit with HST (Nichols et al., 2015)> constraints on Bond albedo and day–night heat transport from secondary eclipse depths (Schwartz & Cowan, 2015)> magnetospheric models, bow shocks, and near-ultraviolet absorption (Alexander et al., 2016)> C/O ratio, and CO, CO<sub>2</sub>, and H<sub>2</sub>O abundances (Heng & Lyons, 2016)> ultraviolet light curves attributed to outgassing from Trojan satellites on tadpole orbits (Kislyakova et al., 2016)> new transit times from 2012–16 suggestive of tidal decay (Maciejewski et al., 2016a)> H<sub>2</sub>O in clear/cloudy atmospheres from infrared transit spectroscopy (Sing et al., 2016)> near ultraviolet transit depth attributed to planet atmosphere (Turner et al., 2016a)> envelope enrichment and predicted H<sub>2</sub>O abundance (Venturini et al., 2016)> reduction of mass loss due to magnetic field (Arakcheev et al., 2017)> atmospheric retrieval analysis with NEMESIS (Barstow et al., 2017)> very low albedo,  $A_g < 0.064$ , from spectral eclipse with HST-STIS (Bell et al., 2017)> effect of dynamical tides excited by gravity waves in the host star on planet’s orbital evolution (Chernov et al., 2017)> limits on transit timing variations (Collins et al., 2017a)> Roche lobe overflow model and mass-loss for short-period gaseous planets (Jackson et al., 2017b)> atmospheric modeling with HELIOS (Malik et al., 2017)> sensitivity of atmospheric models to prior assumptions (Oreshenko et al., 2017)> transit/secondary eclipse favour tidal decay ( $\dot{P} = 29 \pm 3 \text{ ms yr}^{-1}$ ) over apsidal precession (Patra et al., 2017)> phase offsets and energy budgets (Schwartz et al., 2017)> atmospheric clouds associated with metal-rich host star (Wakeford et al., 2017c)> tidal decay model suggest planet is in the last 0.1% of its life (Weinberg et al., 2017)>
- WASP-13** discovery, radial velocity (Skillen et al., 2009)> four transits from RISE, improved ephemeris (Barros et al., 2012)> photometry and new spectroscopy (Southworth, 2012)> parameters from HoSTS (Gómez Maqueo Chew et al., 2013a)> Rossiter–McLaughlin effect from OHP-SOPHIE (Brothwell et al., 2014)> far ultraviolet spectroscopy of host star, irradiance, and planet mass-loss (Fossati et al., 2015a)> low chromospheric activity attributed to intervening ISM absorption (Fossati et al., 2017b)> 4.5  $\mu$ m secondary eclipse depths with Spitzer-IRAC (Kilpatrick et al., 2017)>
- WASP-14** discovery, radial velocity confirmation, high density, and Rossiter–McLaughlin effect (Joshi et al., 2009)> Rossiter–McLaughlin effect (Johnson et al., 2009a)> radial velocities, non-zero eccentricity (Husnoo et al., 2011)> tidal effects on radial velocity (Arras et al., 2012)> tidal effects and spin–orbit alignment from orbit eccentricity (Husnoo et al., 2012)> C/O ratio as a characterisation of atmospheres (Madhusudhan, 2012)> photometry and new spectroscopy (Southworth, 2012)> secondary eclipse from Spitzer (Blecic et al., 2013)> spectroscopic inferences from high-resolution V-band spectrum (Czekala et al., 2015)> transit time analysis of 19 light curves (Raetz et al., 2015)> full-orbit phase curves at 3.6 and 4.5  $\mu$ m with Spitzer (Wong et al., 2015)> nearby star from lucky imaging (Wöllert et al., 2015)> phase curve from sparsely-sampled Spitzer-IRAC observations (Krick et al., 2016)> radial velocity with low-cost échelle spectroscopy at 0.6-m Stará Lesná Observatory, Slovakia (Garai et al., 2017)> atmospheric modeling with HELIOS (Malik et al., 2017)>
- WASP-15** discovery, radial velocity confirmation (West et al., 2009a)> tidal heating (Ibgui et al., 2010)> Rossiter–McLaughlin effect (Triaud et al., 2010)> transits with WHT-ULTRACAM (Bento & Wheatley, 2011)> coupled radius–orbit evolutionary models (Ibgui et al., 2011)> defocused transits from MPG-GROND (Southworth et al., 2013)> 4.5  $\mu$ m secondary eclipse depths with Spitzer-IRAC (Kilpatrick et al., 2017)>
- WASP-16** host star solar analogue; discovery, radial velocity confirmation (Lister et al., 2009)> Rossiter–McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> Rossiter–McLaughlin effect (Brown et al., 2012a)> defocused transits from MPG-GROND (Southworth et al., 2013)> 4.5  $\mu$ m secondary eclipse depths with Spitzer-IRAC (Kilpatrick et al., 2017)>
- WASP-17** retrograde orbit, low density, inflated atmospheric scale height; discovery, radial velocity confirmation, Rossiter–McLaughlin effect, probable retrograde orbit (Anderson et al., 2010b)> Rossiter–McLaughlin effect, confirmed retrograde orbit (Bayliss et al., 2010)> planetary structure in a tidally-relaxed inclined system (Mardling, 2010)> Rossiter–McLaughlin effect, confirmed retrograde orbit (Triaud et al., 2010)> secondary eclipse and marginally eccentric orbit from Spitzer (Anderson et al., 2011e)> transits with ULTRACAM (Bento & Wheatley, 2011)> models of thermal phase variations for eccentric orbits (Cowan & Agol, 2011a)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> high mass loss from extreme ultraviolet and X-ray radiation (Ehrenreich & Désert, 2011)> Na absorption with VLT-GIRAFFE (Wood et al., 2011)> tidal effects and spin–orbit alignment from orbit eccentricity (Husnoo et al., 2012)> four transits confirming large radius and circular orbit (Southworth et al., 2012b)> Na absorption with Magellan-MIKE (Zhou & Bayliss, 2012)> broad H<sub>2</sub>O absorption at 1.4  $\mu$ m from HST-WFC3 (Mandell et al., 2013)> transmission spectrophotometry from NTT-ULTRACAM (Bento et al., 2014)> cloudiness index based on transit radii associated with line centre/wing of Na/K (Heng, 2016)> atmospheric circulation (Kataria et al., 2016)> K detection from transmission spectroscopy with VLT-FORS2 (Sedaghati et al., 2016)> H<sub>2</sub>O in clear/cloudy atmospheres from infrared transit spectroscopy (Sing et al., 2016)> atmospheric retrieval analysis with NEMESIS (Barstow et al., 2017)> limits on low-frequency radio emission (Lynch et al., 2017)>
- WASP-18** massive, hot, short-period planet; discovery, radial velocity, tidal decay (Hellier et al., 2009a)> 5 transits (Southworth et al., 2009b)> homogeneous analysis and light curve properties (Southworth, 2010)> Rossiter–McLaughlin effect (Triaud et al., 2010)> transit time variations due to stellar quadrupole (Watson & Marsh, 2010)> tidal interaction and stellar spin-up (Brown et al., 2011a)> reflection effect (Budaj, 2011)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> secondary eclipse from Spitzer (Nymeyer et al., 2011)> prospects for detecting bow shocks (Vidotto et al., 2011a)> tidal effects on radial velocity (Araras et al., 2012)> Rossiter–McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> tidal effects and spin–orbit alignment from orbit eccentricity (Husnoo et al., 2012)> non-detection of star–planet interactions (Miller et al., 2012)> photometry and new spectroscopy (Southworth, 2012)> atmospheric heat redistribution (Iro & Maxted, 2013)> orbit and secondary eclipse from Spitzer (Maxted et al., 2013b)> atmospheric heat redistribution efficiency drops as stellar insolation rises (Perez-Becker & Showman, 2013)> predicted shift in transit mid-time due to tidal decay of  $36 \text{ s yr}^{-1}$  (Birkby et al., 2014)> absorbing gas from stellar irradiation responsible for low stellar activity index (Fossati et al., 2014a)> observations from ASTEP, Antarctic (Fruth et al., 2014)> age and activity from X-ray limits from Chandra (Pillitteri et al., 2014b)> limits on radio emission at 154 MHz from the Murchison Widefield Array (Murphy et al., 2015)> constraints on Bond albedo and day–night heat transport from secondary eclipse depths (Schwartz & Cowan, 2015)> Ks-band secondary eclipse observations with AAT-IRIS2 (Zhou et al., 2015b)> magnetospheric mod-

- els, bow shocks, and near-ultraviolet absorption (Alexander et al., 2016)> effect of dynamical tides excited by gravity waves in the host star on planet's orbital evolution (Chernov et al., 2017)> evidence for day-side thermal inversion from HST and Spitzer secondary eclipse (Sheppard et al., 2017)> no signature of rapid orbital decay (Wilkins et al., 2017)> H<sup>+</sup> opacity and water dissociation in the day-side atmosphere (Arcangeli et al., 2018)> suppressed far-UV stellar activity and low planetary mass loss (Fossati et al., 2018)> pre-discovery transits from Hipparcos (McDonald & Kerins, 2018)>
- WASP-19** very short-period ( $P = 0.79$  d) planet; discovery, radial velocity confirmation, stellar rotation, tidal spin-up (Hebb et al., 2010)> secondary eclipse from VLT-HAWK-I (Anderson et al., 2010a)> secondary eclipse from VLT-HAWK-I (Gibson et al., 2010a)> tidal interaction and stellar spin-up (Brown et al., 2011a)> reflection effect (Budaj, 2011)> TERMS photometry (Dragomir et al., 2011)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> Rossiter-McLaughlin effect, third-body interactions, tidal decay (Hellier et al., 2011a)> prospects for detecting bow shocks (Vidotto et al., 2011a)> tidal effects on radial velocity (Arras et al., 2012)> Rossiter-McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> secondary eclipse from NTT-ULTRACAM (Burton et al., 2012)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> C/O ratio as a characterisation of atmospheres (Madhusudhan, 2012)> evidence of secondary eclipse from Antarctic ASTEP 400 (Abe et al., 2013c)> Spitzer-IRAC confirms temperature inversions suppressed in hot Jupiters orbiting active stars (Anderson et al., 2013)> transmission and emission spectra from Magellan-MMIRS (Bean et al., 2013)> H<sub>2</sub>O and TiO limits from HST-STIS (Huitson et al., 2013)> 14 transits and improved system parameters (Lendl et al., 2013)> atmospheric disequilibrium diagnostics (Line & Yung, 2013)> broad 1.4  $\mu\text{m}$  H<sub>2</sub>O absorption from HST-WFC3 (Mandell et al., 2013)> multicolour photometry from Perth-PEST and MPG-GROND (Mancini et al., 2013a)> star spots and spin-orbit projection (Tregloan-Reed et al., 2013)> secondary eclipse from Faulkes South (Zhou et al., 2013)> effects of planet tidal distortion (Burton et al., 2014)> atmospheric disequilibrium diagnostics (Line et al., 2014)> orbital decay driven by tidal dissipation (Valsecchi & Rasio, 2014a)> Ks-band secondary eclipse from AAT-IRIS2 (Zhou et al., 2014b)> gyrochronology and isochrone ages (Maxted et al., 2015b)> transmission spectroscopy using VLT-KMOS (Parviainen et al., 2015)> optical ground-based transmission spectroscopy with VLT-FORS2 (Sedaghati et al., 2015)> orbital decay due to non-linear tidal dissipation, with expected detection within 2–3 yr (Essick & Weinberg, 2016)> atmospheric circulation (Kataria et al., 2016)> H<sub>2</sub>O in clear/cloudy atmospheres from infrared transit spectroscopy (Sing et al., 2016)> 3.6 and 4.5  $\mu\text{m}$  Spitzer phase curves (Wong et al., 2016)> atmospheric retrieval analysis with NEMESIS (Barstow et al., 2017)> unsupervised correlated noise removal for transit light curve fitting (Dehghan Firoozabadi et al., 2017)>
- WASP-20** close visual binary with a transiting hot Jupiter; discovery, Rossiter-McLaughlin effect (Anderson et al., 2015a)> stellar binary with separation 0.26 arcsec (60 au) with planet probably orbiting the primary (Evans et al., 2016b)>
- WASP-21** discovery, radial velocity confirmation (Bouchy et al., 2010)> transits and ephemeris from RISE (Barros et al., 2011b)> photometry and spectroscopy (Southworth, 2012)> transits with two telescopes (Ciceri et al., 2013)> ground-based transits (Seeliger et al., 2015)>
- WASP-22** discovery, radial velocity confirmation, probable orbit around one component of stellar binary (Maxted et al., 2010b)> Rossiter-McLaughlin effect from ESO-HARPS and others (Anderson et al., 2011b)> high-precision photometry from defocused observations with ESO-DFOC (Southworth et al., 2016)>
- WASP-23** discovery, radial velocity confirmation, Rossiter-McLaughlin effect (Triaud et al., 2011)> optical-infrared spectrum from MPG-GROND (Nikolov et al., 2013)>
- WASP-24** discovery, radial velocity (Street et al., 2010)> Rossiter-McLaughlin effect from OHP-SOPHIE (Simpson et al., 2011c)> secondary eclipse and atmospheric modeling from Spitzer (Smith et al., 2012b)> defocused transits, lucky imaging excludes nearby stars (Southworth et al., 2014)> new photometry and atmospheric models (Turner et al., 2017)>
- WASP-25** discovery, radial velocity (Enoch et al., 2011b)> polarisation studies (Kostogryz et al., 2011)> Rossiter-McLaughlin effect (Brown et al., 2012a)> defocused transit observations, lucky imaging excludes nearby stars (Southworth et al., 2014)>
- WASP-26** discovery, radial velocity (Smalley et al., 2010)> Rossiter-McLaughlin effect from HARPS and others (Anderson et al., 2011b)> Rossiter-McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> transmission photometry with Spitzer (Mahtani et al., 2013)> defocused transits, lucky imaging excludes nearby stars (Southworth et al., 2014)>
- WASP-27** see HAT-P-14
- WASP-28**  $\approx$  K2-1; discovery and Rossiter-McLaughlin effect (Anderson et al., 2015a)> transit timing analysis (Petrucci et al., 2015)> additional transit observations (Maciejewski et al., 2016b)> star spots and obliquity from K2 (Močnik et al., 2017a)>
- WASP-29** discovery, radial velocity (Hellier et al., 2010)> TERMS photometry (Dragomir et al., 2011)> transmission spectroscopy from Gemini-MOS (Gibson et al., 2013a)>
- WASP-30** not in NASA; brown dwarf, 61M<sub>J</sub> (Anderson et al., 2011c)> Rossiter-McLaughlin effect (Triaud et al., 2013b)>
- WASP-31** discovery, radial velocity (Anderson et al., 2011d)> TERMS photometry (Dragomir et al., 2011)> Rossiter-McLaughlin effect from Magellan, Keck (Albrecht et al., 2012b)> Rossiter-McLaughlin effect (Brown et al., 2012a)> transmission spectral survey in optical with HST and infrared with Spitzer, and detection of K (Sing et al., 2015)> cloudiness index based on transit radii associated with line centre/wing of Na/K (Heng, 2016)> atmospheric circulation (Kataria et al., 2016)> cloud deck and Rayleigh scattering, but no K, from VLT-FORS2 transmission spectroscopy (Gibson et al., 2017)> H<sub>2</sub>O in clear/cloudy atmospheres from infrared transit spectroscopy (Sing et al., 2016)> atmospheric retrieval analysis with NEMESIS (Barstow et al., 2017)> evidence of N chemistry (NH<sub>3</sub>) from HST-WFC3 (MacDonald & Madhusudhan, 2017b)>
- WASP-32** discovery, radial velocity (Maxted et al., 2010a)> Rossiter-McLaughlin effect (Brown et al., 2012b)> Rossiter-McLaughlin effect from OHP-SOPHIE (Brothwell et al., 2014)> transit timing and homogeneous studies (Sun et al., 2015)> spectroscopic transit observations with Russian BTA telescope (Grauzhanina et al., 2017)>
- WASP-33** short period ( $P = 1.2$  d) hot planet orbiting  $\delta$  Sco star; discovery, radial velocity confirmation, line-profile tomography, projected obliquity, tidal excitation of stellar pulsations (Collier Cameron et al., 2010b)> reflection effect (Budaj, 2011)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> 68 min pulsations of host star (Herrero et al., 2011)> nodal precession (Iorio, 2011b)> possible companion from Keck adaptive optics (Moya et al., 2011)> secondary eclipse, stellar pulsations (Smith et al., 2011)> tidal effects on radial velocity (Arras et al., 2012)> secondary eclipses and atmospheric modeling from Spitzer (Deming et al., 2012)> C/O ratio as a characterisation of atmospheres (Madhusudhan, 2012)> secondary eclipses from WHT-LIRIS (de Mooij et al., 2013b)> pulsation, orbit periods, possible star spots (Kovács et al., 2013b)> host star pulsations from 457 h of small telescope photometry, limits on star-planet interactions (von Essen et al., 2014)> favourable for polarisation studies (Wiktorowicz & Laughlin, 2014)> transit observations with WHT-pt5m (Hardy et al., 2015)> spectroscopic evidence for temperature inversion in day-side atmosphere (Haynes et al., 2015)> nodal precession from Doppler tomography (Johnson et al., 2015a)> pulsation frequency analysis and revised mass (Lehmann et al., 2015)> temperature inversion from secondary eclipse with LBT (von Essen et al., 2015)> stellar and orbit parameters from orbital dynamics (Iorio, 2016)> no asymmetry in ground-based ultraviolet transits (Turner et al., 2016b)> atmospheric modeling with HELIOS (Malik et al., 2017)> inversion and TiO molecular absorption from Subaru-HDS (Nugroho et al., 2017)> pre-discovery transits from Hipparcos (McDonald & Kerins, 2018)> phase curves and albedo from Spitzer photometry (Zhang et al., 2018a)>
- WASP-34** near-grazing transit, in hierarchical triple system; discovery, radial velocity (Smalley et al., 2011a)> favourable for polarisation studies (Wiktorowicz & Laughlin, 2014)>
- WASP-35** discovery, radial velocity (Enoch et al., 2011a)>
- WASP-36** discovery, radial velocity (Smith et al., 2012a)> Ks-band secondary eclipse observations with AAT-IRIS2 (Zhou et al., 2015b)> new transit observations (Maciejewski et al., 2016b)> 5 new multicolour transits and constraints on transmission spectrum (Mancini et al., 2016b)> orbital decay due to non-linear tidal dissipation (Essick & Weinberg, 2016)> no asymmetry in ground-based ultraviolet transits (Turner et al., 2016b)>
- WASP-37** low-metallicity star; radial velocity (Simpson et al., 2011b)>

- WASP-38** discovery, radial velocity (Barros et al., 2011a)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> Rossiter–McLaughlin effect from OHP-SOPHIE (Simpson et al., 2011c)> Rossiter–McLaughlin effect from OHP-SOPHIE (Brown et al., 2012b)>
- WASP-39** discovery, radial velocity (Faedi et al., 2011a)> Spitzer secondary eclipse observations at 3.6 and 4.5  $\mu\text{m}$  (Kammer et al., 2015)> multicolour transit observations (Ricci et al., 2015)> Rayleigh scattering with Na and K absorption from HST-STIS (Fischer et al., 2016b)> atmospheric circulation (Kataria et al., 2016)> additional transit observations (Maciejewski et al., 2016b)> improved transit ephemeris (Maciejewski et al., 2016c)> transmission spectroscopy with Na absorption from VLT-FORS2 (Nikolov et al., 2016)> H<sub>2</sub>O in clear/cloudy atmospheres from infrared transit spectroscopy (Sing et al., 2016)> atmospheric retrieval analysis with NEMESIS (Barstow et al., 2017)> three near-infrared H<sub>2</sub>O-absorption features and  $T_{\text{eq}} = 1030^{+30}_{-20}$  K from HST-WFC3 (Wakeford et al., 2018)>
- WASP-40** see HAT-P-27
- WASP-41** 2-planet system, inner (planet b) discovered from transits, outer (planet c) from radial velocity; discovery of planet b and radial velocity confirmation with CORALIE (Maxted et al., 2011)> gyrochronology and isochrone ages (Maxted et al., 2015b)> refined physical properties (Vaňko et al., 2015)> discovery of planet c from radial velocity, and Rossiter–McLaughlin effect (Neveu-VanMalle et al., 2016)> high-precision photometry from defocussed observations with ESO-DFOC (Southworth et al., 2016)> modeling of star spots using PyTranSpot (Juvan et al., 2018)>
- WASP-42** discovery, radial velocity (Lendl et al., 2012)> high-precision photometry from defocussed observations with ESO-DFOC (Southworth et al., 2016)>
- WASP-43** very short-period ( $P = 0.81$  d) hot Jupiter orbiting cool low-mass star; discovery, radial velocity (Hellier et al., 2011b)> tidal effects on radial velocity (Arras et al., 2012)> 23 transits and 7 secondary eclipses from TRAPPIST (Gillon et al., 2012b)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> X-ray emission and inferred mass loss from XMM-Newton (Czesla et al., 2013)> atmospheric disequilibrium diagnostics (Line & Yung, 2013)> transit times from 2009–2013 consistent with linear ephemeris (Maciejewski et al., 2013c)> secondary eclipse from CFHT-WIRCam (Wang et al., 2013c)> constraints from Spitzer secondary eclipse (Blecic et al., 2014)> transit and secondary eclipse from MPG-GROND (Chen et al., 2014c)> tidal evolution (Dong, 2014)> H<sub>2</sub>O content from HST-WFC3 consistent with solar composition (Kreidberg et al., 2014a)> atmospheric disequilibrium (Line et al., 2014)> transit spectroscopy from GTC-OSIRIS (Murgas et al., 2014)> emission spectroscopy over three planet rotations from HST-WFC3 (Stevenson et al., 2014d)> Ks-band secondary eclipse from AAT-IRIS2 (Zhou et al., 2014b)> atmospheric circulation (Kataria et al., 2015)> multicolour transit observations (Ricci et al., 2015)> high-energy irradiation and mass-loss rates (Salz et al., 2015)> constraints on Bond albedo and day-night heat transport from secondary eclipse depths (Schwartz & Cowan, 2015)> transits observed with SAO 1-m telescope (Valyavin et al., 2015b)> effect of non-uniform thermal structure on emission spectrum (Feng et al., 2016b)> 15 new transits constrain negative rapid orbital decay (Hoyer et al., 2016b)> orbital period decay rate  $-0.029 \pm 0.007 \text{ s yr}^{-1}$  (Jiang et al., 2016)> envelope enrichment and predicted H<sub>2</sub>O abundance (Venturini et al., 2016)> effect of dynamical tides excited by gravity waves in the host star on planet's orbital evolution (Chernov et al., 2017)> Rossiter–McLaughlin effect and orbital obliquity from HARPS-N (Esposito et al., 2017)> models of day-night temperature contrast (Keating & Cowan, 2017)> phase curve and secondary eclipse modeled with SPIDERMAN, and the inference of clouds (Louden & Kreidberg, 2017)> atmospheric modeling with HELIOS (Malik et al., 2017)> chromospheric activity, mass loss, and star-planet interaction (Staab et al., 2017)> Spitzer phase curve constraints at 3.6 and 4.5  $\mu\text{m}$  (Stevenson et al., 2017)> atmospheric structure and dynamics from Doppler-shifted emission spectra (Zhang et al., 2017a)> confronting re-analysed Spitzer data with cloudy atmospheres (Mendonça et al., 2018)> photometric follow-up and transit timing analysis with the Xuyi Near-Earth Object Survey Telescope (Zhao et al., 2018b)>
- WASP-44** discovery, radial velocity (Anderson et al., 2012)> multicolour photometry and improved radius (Mancini et al., 2013b)> multicolour characterisation (Moyano et al., 2017)>
- WASP-45** discovery, radial velocity (Anderson et al., 2012)> system properties from multi-colour photometry (Ciceri et al., 2016b)>
- WASP-46** discovery, radial velocity (Anderson et al., 2012)> thermal day-side emission from MPG-GROND (Chen et al., 2014d)> transits with 0.4-m telescope (Kjurkchieva et al., 2015)> gyrochronology and isochrone ages (Maxted et al., 2015b)> Ks-band secondary eclipse observations with AAT-IRIS2 (Zhou et al., 2015b)> system properties from multi-colour photometry (Ciceri et al., 2016b)> multicolour characterisation (Moyano et al., 2017)> limits on transit timing variations and orbit decay (Petrucci et al., 2018)>
- WASP-47**  $\equiv$  K2-23; 4-planet system, planet b transiting, planet c from radial velocity, and planets d and e also transiting; discovery of planet b and radial velocity confirmation with CORALIE (Hellier et al., 2012)> two additional transiting planets (d and e) from K2, transit time variations (Becker et al., 2015)> radial velocity monitoring with Magellan-PFS (Dai et al., 2015)> Rossiter–McLaughlin effect and low stellar obliquity (Sanchis-Ojeda et al., 2015b)> densities, masses and radii from dynamical modeling (Almenara et al., 2016)> representing the extended tail of *in situ* formation warm Jupiters into the hot Jupiter region (Huang et al., 2016)> discovery/confirmation of planet c from radial velocity (Neveu-VanMalle et al., 2016)> effect of unseen additional perturber (Becker & Adams, 2017)> mass constraints from radial velocities (Sinukoff et al., 2017b)> precise masses from HARPS-N (Vanderburg et al., 2017)> hot Jupiter migration attributed to disk interactions (Wang et al., 2017d)> analysis of radial velocities and transit timing variations (Weiss et al., 2017)>
- WASP-48** discovery, radial velocity (Enoch et al., 2011a)> secondary eclipses and eccentricity from Spitzer-IRAC and Palomar-WFIRCAM (O'Rourke et al., 2014)> physical properties from multicolour photometry (Ciceri et al., 2015b)> no asymmetry in ground-based ultraviolet transits (Turner et al., 2016b)> transmission spectrum from GCT-OSIRIS (Murgas et al., 2017)>
- WASP-49** discovery, radial velocity (Lendl et al., 2012)> atmospheric properties from transmission spectroscopy with VLT-FORS2 (Lendl et al., 2016)> aerosol constraints (Cubillos et al., 2017d)> transmission spectroscopy and Rossiter–McLaughlin effect from HARPS (Wytenbach et al., 2017)>
- WASP-50** discovery, radial velocity (Gillon et al., 2011b)> tidal evolution (Dong & Ji, 2012)> defocused transits with NTT-EFOSC2 (Tregloan-Reed & Southworth, 2013)> gyrochronology and isochrone ages (Maxted et al., 2015b)>
- WASP-51** see HAT-P-30
- WASP-52** discovery, radial velocity, Rossiter–McLaughlin effect (Hébrard et al., 2013b)> compilation of light curves and transit timing (Baluev et al., 2015)> transit observations with MINERVA (Swift et al., 2015a)> transmission spectrum with WHT-ULTRACAM indicates stellar bright spot (Kirk et al., 2016b)> orbital alignment and star-spot properties (Mancini et al., 2017)> atmospheric Na absorption with GTC-OSIRIS (Chen et al., 2017b)> optical transmission spectrum 400–875 nm from WHT (Louden et al., 2017b)>
- WASP-53** 2-planet system: transiting hot Jupiter with additional transiting brown dwarf (planet c,  $> 16M_{\text{J}}$ ) on highly-eccentric ( $e = 0.84$ ) orbit; discovery and Rossiter–McLaughlin effect (Triaud et al., 2017b)>
- WASP-54** discovery, radial velocity (Faedi et al., 2013a)> improved orbit from HARPS-N (Bonomo et al., 2017a)>
- WASP-55** discovery, radial velocity (Hellier et al., 2012)> recovery from K2SC pipeline processing (Pope et al., 2016)> high-precision photometry from defocussed observations with ESO-DFOC (Southworth et al., 2016)> variability, star spots and rotation from K2 (Clark et al., 2018)>
- WASP-56** discovery, radial velocity (Faedi et al., 2013a)> nearby star from lucky imaging (Wöllert & Brandner, 2015)>
- WASP-57** discovery, radial velocity (Faedi et al., 2013a)> revised properties and shorter orbital period (Southworth et al., 2015b)>
- WASP-58** discovery, radial velocity (Hébrard et al., 2013b)> nearby star from lucky imaging (Wöllert et al., 2015)>
- WASP-59** discovery, radial velocity (Hébrard et al., 2013b)>
- WASP-60** discovery, radial velocity (Hébrard et al., 2013b)> new photometry and atmospheric models (Turner et al., 2017)>
- WASP-61** discovery, radial velocity (Hellier et al., 2012)> Rossiter–McLaughlin models and their effect on estimates of stellar rotation (Brown et al., 2017a)>

- WASP-62** discovery, radial velocity (Hellier et al., 2012)> favourable for lightning-discharge studies (Hodosán et al., 2016a)> candidate for JWST (Stevenson et al., 2016b)> Rossiter-McLaughlin models and effect on stellar rotation estimates (Brown et al., 2017a)> 4.5  $\mu\text{m}$  secondary eclipse depths with Spitzer-IRAC (Kilpatrick et al., 2017)>
- WASP-63** discovery, radial velocity (Hellier et al., 2012)> N chemistry (HCN) from HST-WFC3 (MacDonald & Madhusudhan, 2017b)>
- WASP-64** discovery, radial velocity (Gillon et al., 2013a)>
- WASP-65** discovery, radial velocity (Gómez Maqueo Chew et al., 2013b)>
- WASP-66** discovery, radial velocity (Hellier et al., 2012)> Rossiter-McLaughlin effect from AAT-UCLES (Addison et al., 2016)>
- WASP-67** discovery, radial velocity (Hellier et al., 2012)> grazing transits and multicolour photometry with MPG-GROND (Mancini et al., 2014b)> Spitzer secondary eclipse at 3.6 and 4.5  $\mu\text{m}$  (Kammer et al., 2015)> cloud model from HST-WFC3 (Bruno et al., 2018)>
- WASP-68** discovery, radial velocity (Delrez et al., 2014)>
- WASP-69** discovery, radial velocity, X-ray induced high evaporation rate (Anderson et al., 2014b)> gyrochronology and isochrone ages (Maxted et al., 2015b)> favourable for lightning-discharge studies (Hodosán et al., 2016a)> atmospheric Na, and Rossiter-McLaughlin effect from HARPS-N (Casasayas-Barris et al., 2017)>
- WASP-70A** planet orbits the evolved primary of a G4+K3 binary; discovery, radial velocity (Anderson et al., 2014b)>
- WASP-71** discovery, radial velocity, and Rossiter-McLaughlin effect (Smith et al., 2013)> Rossiter-McLaughlin models and their effect on estimates of stellar rotation (Brown et al., 2017a)>
- WASP-72** discovery, radial velocity (Gillon et al., 2013a)> chromospheric activity, mass loss, and star-planet interaction (Staab et al., 2017)>
- WASP-73** discovery, radial velocity (Delrez et al., 2014)>
- WASP-74** discovery, radial velocity (Hellier et al., 2015)>
- WASP-75**  $\equiv$  K2-40; discovery, radial velocity (Gómez Maqueo Chew et al., 2013b)> independent discovery by K2 (Crossfield et al., 2016)> variability, star spots and rotation from K2 (Clark et al., 2018)>
- WASP-76** discovery, radial velocity (West et al., 2016a)> nearby star from lucky imaging (Wöllert & Brandner, 2015)> Ks-band secondary eclipse observations with AAT-IRIS2 (Zhou et al., 2015b)> confirmed stellar companion from lucky imaging (Ginski et al., 2016a)> Rossiter-McLaughlin models and their effect on estimates of stellar rotation (Brown et al., 2017a)>
- WASP-77A** discovery, radial velocity (Maxted et al., 2013a)> possible radio detection with VLA FIRST (Sirothia et al., 2014)> gyrochronology and isochrone ages (Maxted et al., 2015b)> high-energy irradiation and mass-loss rates (Salz et al., 2015)> no asymmetry in ground-based ultraviolet transits (Turner et al., 2016b)>
- WASP-78** very hot Jupiter; discovery, radial velocity (Smalley et al., 2012)> Rossiter-McLaughlin models and their effect on estimates of stellar rotation (Brown et al., 2017a)>
- WASP-79** largest WASP planet (2.1  $R_J$ ); discovery, radial velocity (Smalley et al., 2012)> Rossiter-McLaughlin effect indicating near-polar orbit from AAT-UCLES (Addison et al., 2013)> favourable for polarisation studies (Wiktorowicz & Laughlin, 2014)> Rossiter-McLaughlin models and estimates of stellar rotation (Brown et al., 2017a)> Rossiter-McLaughlin effect (Johnson et al., 2017c)>
- WASP-80** M dwarf host star and large transit depth; discovery, radial velocity, Rossiter-McLaughlin effect (Triaud et al., 2013a)> five transits (Fukui et al., 2014)> transmission spectrum from multicolour photometry (Mancini et al., 2014a)> high-energy irradiation and mass-loss rates (Salz et al., 2015)> transit, secondary eclipse, cool day-side temperature, aligned orbit from Spitzer (Triaud et al., 2015)> atmospheric escape of hot gas coupling plasma, photoionisation and Ly- $\alpha$  emission (Salz et al., 2016)> photometric observations and transit solutions (Kjurkchieva et al., 2017b)> atmospheric properties from VLT-FORS2 transmission spectrum (Sedaghati et al., 2017)> new photometry and atmospheric models (Turner et al., 2017)> transmission spectrum from WHT-ACAM consistent with haze (Kirk et al., 2018)> flat transmission spectrum from GTC-OSIRIS (Parviainen et al., 2018)>
- WASP-81** transiting hot Jupiter with additional brown dwarf on eccentric orbit (Triaud et al., 2017b)>
- WASP-82** discovery, radial velocity (West et al., 2016a)> revised properties (Smith, 2015)>
- WASP-83** discovery, radial velocity (Hellier et al., 2015)>
- WASP-84** long period; discovery, radial velocity (Anderson et al., 2014b)> Rossiter-McLaughlin effect and implications for migration history from HARPS-N (Anderson et al., 2015b)> gyrochronology and isochrone ages (Maxted et al., 2015b)>
- WASP-85A**  $\equiv$  K2-94; discovery and occultation of star spots (Močnik et al., 2016b)> gyrochronology and isochrone ages (Maxted et al., 2015b)> improved ground-based transit photometry using beam-shaping diffusers (Stefansson et al., 2017)>
- WASP-86** in preparation
- WASP-87** not in NASA (end 2017); discovery (Anderson et al., 2014a)> Rossiter-McLaughlin effect from AAT-UCLES (Addison et al., 2016)>
- WASP-88** discovery, radial velocity (Delrez et al., 2014)>
- WASP-89** discovery, radial velocity, star spots (Hellier et al., 2015)> gyrochronology and isochrone ages (Maxted et al., 2015b)>
- WASP-90** discovery, radial velocity (West et al., 2016a)>
- WASP-91** discovery, radial velocity (Anderson et al., 2017a)>
- WASP-92** discovery (Hay et al., 2016)>
- WASP-93** discovery (Hay et al., 2016)>
- WASP-94A** two hot-Jupiters, each orbiting one component of 15 arcsec binary (WASP-94A and WASP-94B); WASP-94A b transits, WASP-94B b does not transit and discovered from radial velocity; mutual inclination indicates at least one inclined to stellar binary plane; discovery of both planets, radial velocities, and Rossiter-McLaughlin effect for WASP-94A b (Neveu-VanMalle et al., 2014)> unexplained stellar elemental abundance differences (Teske et al., 2016a)>
- WASP-95** discovery, radial velocity (Hellier et al., 2014)>
- WASP-96** discovery, radial velocity (Hellier et al., 2014)>
- WASP-97** discovery, radial velocity (Hellier et al., 2014)>
- WASP-98** hot Jupiter orbiting a metal-poor main-sequence star; discovery, radial velocity (Hellier et al., 2014)> optical transmission spectrum (Mancini et al., 2016a)>
- WASP-99** discovery, radial velocity (Hellier et al., 2014)>
- WASP-100** discovery, radial velocity (Hellier et al., 2014)>
- WASP-101** discovery, radial velocity (Hellier et al., 2014)> absence of H<sub>2</sub>O from HST-PanCET programme, and candidate for JWST (Wakeford et al., 2017b)>
- WASP-102** in preparation
- WASP-103** short period (0.93 d) large radius planet close tidal disruption; discovery, radial velocity (Gillon et al., 2014a)> high-precision photometry by telescope defocusing (Southworth et al., 2015a)> nearby star from lucky imaging (Wöllert & Brandner, 2015)> Rossiter-McLaughlin effect from AAT-UCLES (Addison et al., 2016)> anomalous transmission spectrum (Southworth & Evans, 2016)> near-infrared emission spectrum with HST-WFC3 (Cartier et al., 2017)> strong Na and K absorption from Gemini-GMOS (Lendl et al., 2017a)> chromospheric activity, mass loss, and star-planet interaction (Staab et al., 2017)> new photometry and atmospheric models (Turner et al., 2017)> high-precision multi-wavelength photometry for 3 transits and 16 secondary eclipses (Delrez et al., 2018b)>
- WASP-104** discovery, radial velocity (Smith et al., 2014a)> transits observed with SAO 1-m telescope (Valyavin et al., 2015b)>
- WASP-105** discovery, radial velocity (Anderson et al., 2017a)>
- WASP-106** discovery, radial velocity (Smith et al., 2014a)>
- WASP-107** discovery, radial velocity (Anderson et al., 2017a)> oblique orbit from K2 photometry and star spots (Dai & Winn, 2017)> star spots and rotational period (Močnik et al., 2017b)>
- WASP-108** not in NASA (end 2017); discovery (Anderson et al., 2014a)>
- WASP-109** not in NASA (end 2017); discovery (Anderson et al., 2014a)>
- WASP-110** not in NASA (end 2017); discovery (Anderson et al., 2014a)>
- WASP-111** not in NASA (end 2017); discovery and Rossiter-McLaughlin effect (Anderson et al., 2014a)>
- WASP-112** not in NASA (end 2017); discovery (Anderson et al., 2014a)>
- WASP-113** discovery (Barros et al., 2016a)>
- WASP-114** discovery (Barros et al., 2016a)>
- WASP-115** in preparation
- WASP-116** in preparation
- WASP-117** long period (10 d) eccentric ( $e = 0.3$ ) orbit; discovery, radial velocity, Rossiter-McLaughlin effect (Lendl et al., 2014)>



- WASP-118** discovery (Hay et al., 2016)> star spots and rotational period (Močnik et al., 2017b)>
- WASP-119** discovery (Maxted et al., 2016)>
- WASP-120** discovery (Turner et al., 2016c)>
- WASP-121** highly-irradiated hot Jupiter; discovery and Rossiter-McLaughlin effect (Delrez et al., 2016)> detection of H<sub>2</sub>O and evidence for TiO/VO from HST-WFC3 transit spectroscopy (Evans et al., 2016c)> distinguishing clouds and haze (Kempton et al., 2017a) >
- WASP-122** see KELT-14
- WASP-123** discovery (Turner et al., 2016c)>
- WASP-124** discovery (Maxted et al., 2016)>
- WASP-125** in preparation
- WASP-126** discovery (Maxted et al., 2016)>
- WASP-127** low-density sub-Saturn planet; discovery (Lam et al., 2017)> Rayleigh slope at blue wavelengths, TiO and VO at redder, from NOT-ALFOSC (Palle et al., 2017)>
- WASP-128** in preparation
- WASP-129** discovery (Maxted et al., 2016)>
- WASP-130...WASP-132** discovery (Hellier et al., 2017)>
- WASP-133** discovery (Maxted et al., 2016)>
- WASP-134** in preparation
- WASP-135** discovery, radial velocity, star spin-up (Spake et al., 2016)>
- WASP-136** discovery (Lam et al., 2017)>
- WASP-137** in preparation
- WASP-138** discovery (Lam et al., 2017)>
- WASP-139...WASP-142** discovery (Hellier et al., 2017)>
- WASP-143** in preparation
- WASP-144** discovery (Hellier et al., 2018)>
- WASP-145** discovery (Hellier et al., 2018)>
- WASP-146...WASP-150** in preparation
- WASP-151** ≡ K2-134; discovery (Demangeon et al., 2018)> rotational modulation and star spots from K2 (Močnik et al., 2017a)>
- WASP-152** see K2-29
- WASP-153** discovery (Demangeon et al., 2018)>
- WASP-154** in preparation
- WASP-155** in preparation
- WASP-156** discovery (Demangeon et al., 2018)>
- WASP-157** ≡ K2-41; discovery (Močnik et al., 2016a)>
- WASP-158** discovery (Hellier et al., 2018)>
- WASP-159** discovery (Hellier et al., 2018)>
- WASP-160...WASP-161** in preparation
- WASP-162** discovery (Hellier et al., 2018)>
- WASP-163...WASP-166** in preparation
- WASP-167** ≡ KELT-13; retrograde orbit; discovery and Rossiter-McLaughlin effect (Temple et al., 2017)>
- WASP-168** discovery (Hellier et al., 2018)>
- WASP-169...WASP-171** in preparation
- WASP-172** discovery (Hellier et al., 2018)>
- WASP-173** discovery (Hellier et al., 2018)>
- WTS**
- WTS-1** discovery, radial velocity (Cappetta et al., 2012)>
- WTS-2** 1.0 d planet close to tidal destruction, and predicted orbit decay; discovery (Birkby et al., 2014)>
- XO**
- XO-1** discovery, radial velocity (McCullough et al., 2006)> four transits, improved parameters (Holman et al., 2006)> SuperWasp transits from 2004 (Wilson et al., 2006)> secondary eclipse and atmospheric modeling from Spitzer (Machalek et al., 2008)> homogeneous analysis and light curve properties (Southworth, 2008)> limits on transit time variations (Cáceres et al., 2009)> transits (Raetz et al., 2009b)> light curve properties (Southworth, 2009)> transits from HST-NICMOS (Burke et al., 2010)> homogeneous analysis and light curve properties (Southworth, 2010)> terminator region probed with emission spectroscopy (Tinetti et al., 2010)> atmospheric constraints from archival HST-NICMOS (Gibson et al., 2011b)> C/O ratio as a characterisation of atmospheres (Madhusudhan, 2012)> H<sub>2</sub>O absorption from HST-WFC3 spatial scanning (Deming et al., 2013)> C/O modeling, confirmation of C-rich atmosphere (Moses et al., 2013c)> orbit parameters versus atmospheric species (Miguel & Kaltenegger, 2014)>
- XO-2N** and **XO-2S** binary star system; discovered as hot Jupiter transiting binary component XO-2N (XO-2N planet b); two further planets orbiting XO-2S (planets b and c) discovered from radial velocity monitoring in 2014; discovery, radial velocity and Galactic origin (Burke et al., 2007)> 6 transits (Fernandez et al., 2009)> secondary eclipse and atmospheric models from Spitzer (Machalek et al., 2009)> homogeneous analysis and light curve properties (Southworth, 2010)> transit from IRTF-MORIS (Gulbis et al., 2011)> Rossiter-McLaughlin effect, possible third planet (Narita et al., 2011)> 3 transits and atmospheric K from GTC-OSIRIS (Sing et al., 2011a)> transits observed with Shandong/Weihai 1-m (Zhang et al., 2011)> limits on H<sub>2</sub>O from HST-NICMOS (Crouzet et al., 2012)> tidal effects and spin-orbit alignment from orbit eccentricity (Husnoo et al., 2012)> transits and atmospheric Na from GTC-OSIRIS (Sing et al., 2012)> photometry and new spectroscopy (Southworth, 2012)> 10 transits, limits on transit time variations, dynamical stability from Apache Point-APOSTLE (Kundurthy et al., 2013a)> host star abundances (Teske et al., 2013b)> two further planets orbiting binary component XO-2S from radial velocity with HARPS-N (Desidera et al., 2014)> radial velocity search for massive long-period companion (Knutson et al., 2014c)> effects of photoionisation on transit depth in K (Lavas et al., 2014)> compilation of light curves and transit timing (Baluev et al., 2015)> abundance differences in the binary components from HARPS-N (Biazzo et al., 2015)> comprehensive analysis with HARPS-N (Damasso et al., 2015a)> abundance differences through early metal depletion or late stage accretion (Ramírez et al., 2015)> abundance differences as a probe of giant planet formation (Teske et al., 2015b)> host star variability (Zellem et al., 2015)> photometric observations and transit solutions (Kjurkchieva et al., 2017b)>
- XO-3** high mass and large eccentricity; discovery, radial velocity (Johns-Krull et al., 2008)> Rossiter-McLaughlin effect (Hébrard et al., 2008)> modeling of radius (Liu et al., 2008a)> 13 transits and improved radius (Winn et al., 2008d)> Rossiter-McLaughlin effect (Winn et al., 2009e)> secondary eclipse, eccentricity, atmospheric modeling from Spitzer (Machalek et al., 2010)> homogeneous analysis and light curve properties (Southworth, 2010)> thermal phase variations for eccentric orbits (Cowan & Agol, 2011a)> predicted transit duration variations due to apsidal and nodal precession (Damiani & Lanza, 2011)> Rossiter-McLaughlin effect, possible third planet, stellar differential rotation (Hirano et al., 2011a)> tidal effects on radial velocity (Arras et al., 2012)> post-Newtonian effects (Li, 2012b)> stellar magnetic field topology (Fares et al., 2013)> 12 secondary eclipses and limits on pericentre precession from Spitzer-IRC (Wong et al., 2014)> re-analysis of Spitzer-IRAC secondary eclipse observations, and comparison of analysis methods (Ingalls et al., 2016)> radial velocity with low-cost échelle spectroscopy at 0.6-m Stará Lesná Observatory, Slovakia (Garai et al., 2017)> new photometry and atmospheric models (Turner et al., 2017)>
- XO-4** discovery, radial velocity (McCullough et al., 2008)> Rossiter-McLaughlin effect (Narita et al., 2010a)> homogeneous analysis and light curve properties (Southworth, 2010)> photometry and new spectroscopy (Southworth, 2011)> atmospheric constraints from Spitzer-IRAC (Todorov et al., 2012)> 7 new transits from DEMONEX (Villanueva et al., 2016)>
- XO-5** high Safronov number, high surface gravity; discovery, radial velocity (Burke et al., 2008)> confirmation from spectral bisector (Pál et al., 2009)> homogeneous analysis and light curve properties (Southworth, 2010)> infrared excess suggesting debris disk from WISE (Krivov et al., 2011)> transits and system parameters (Maciejewski et al., 2011d)> revised properties (Smith, 2015)>
- XO-6** hot Jupiter on an oblique orbit around a fast-rotating F star; discovery (Crouzet et al., 2017)>



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# Appendix E. Lensing exoplanets

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This appendix includes objects appearing in the online NASA Exoplanet Archive as of 31 December 2017.

These notes list some key attributes of the system to underline its particular interest, give some indication of the attention the object has received (through the length of the bibliography), and provide a concise note on each paper to serve as a guide to the literature and a narrative of the progress in understanding the system. It makes no claim for completeness, and CDS–SIMBAD should be consulted for more details.

It includes only cross-identifications which are relevant in context, e.g., as used in the early discovery literature. CDS–SIMBAD or the NASA Exoplanet Archive should be consulted for other aliases. If a different alias was used in the NASA Exoplanet Archive, this is explicitly noted.

The electronic version includes three classes of hyperlink: the object identifier (in bold) is linked to the host star page of the NASA Exoplanet Archive (it will be invalid if their syntax changes); each citation is linked to the bibliography; and the > icon following the citation links to the relevant ADS page.

Ordering is by the designated system/planet name, generally related to the event occurrence. The discovery reference can be some years following the event.

## Notes on individual systems

- MOA-2007-BLG-192L** inclusion of parallax and finite source effects, and VLT-NACO imaging (Bennett et al., 2008)> photometric alignment of multi-site microlensing light curves (Gould et al., 2010a)> detection of light from host star with VLT-NACO (Kubas et al., 2012)>
- MOA-2007-BLG-197L** brown dwarf companion in the brown dwarf desert; not in NASA Exoplanet Archive; discovery (Ranc et al., 2015)>
- MOA-2007-BLG-400L**  $A_{\max} \sim 600$  (Dong et al., 2009a)>
- MOA-2008-BLG-310L**  $D_L \gtrsim 6$  kpc implying the first planet found within the Galactic bulge (Janczak et al., 2010)> 2-epoch HST observations show that the star blended with the source is not the lens star (Bhattacharya et al., 2017)>
- MOA-2008-BLG-379L** faint source star crossing the large resonant caustic (Suzuki et al., 2014)>
- MOA-2009-BLG-266L** system masses from microlens parallax light curve distortion due to orbital motion of Earth and EPOXI satellite (Muraki et al., 2011)>
- MOA-2009-BLG-319L** discovered from MOA-II survey monitoring, with identification as a high-magnification event 24 h prior to its peak (Miyake et al., 2011)>
- MOA-2009-BLG-387L** M star host with pronounced deviations over 12 d with mass from Earth orbital motion (Batista et al., 2011)>
- MOA-2010-BLG-073L** long event crossing time,  $t_E = 44.3$  d, allowing detection of orbital motion (Street et al., 2013) >
- MOA-2010-BLG-117L** not in NASA Exoplanet Archive; the first planetary microlensing event ( $M_p = 0.5M_J$ ,  $M_* = 0.6M_\odot$ ) with a binary source star (Bennett et al., 2018)>
- MOA-2010-BLG-328L** sub-Neptune-mass planet orbiting a very late M dwarf (Furusawa et al., 2013) >
- MOA-2010-BLG-353L** Saturn-mass planet orbiting an M dwarf (Rattenbury et al., 2015)>
- MOA-2010-BLG-477L** high-magnification event modeled with Bayesian priors on Galactic model and planet orbit (Bachelet et al., 2012b)>
- MOA-2011-BLG-028L** Neptune-mass planet orbiting a  $0.8M_\odot$  star in the Galactic bulge (Skowron et al., 2016)>
- MOA-2011-BLG-262L** first free-floating exoplanet–exomoon candidate (Bennett et al., 2014)> determination of source proper motion (Skowron et al., 2014)>
- MOA-2011-BLG-293L** first lensing planet based on second-generation survey (Yee et al., 2012)> Keck adaptive optics placing planet in habitable zone (Batista et al., 2014)>
- MOA-2011-BLG-322L** first microlensing planet based solely on second-generation survey data (Shvartzvald et al., 2014)>
- MOA-2012-BLG-006L** planet or brown dwarf mass companion on a wide orbit (Poleski et al., 2017)>
- MOA-2012-BLG-505L** super-Earth-mass planet probably in the Galactic bulge (Nagakane et al., 2017)>
- MOA-2013-BLG-605L** Neptune or super-Earth planet in a Neptune-like orbit (Sumi et al., 2016)>
- MOA-2016-BLG-227L** large planet/host mass ratio, located near to K2 Campaign 9 (microlensing) field, observed with Keck AO imaging (Koshimoto et al., 2017a)>
- MOA-bin-1L** wide separation planet, found as by-product of a search for short time scale single lens events due to free-floating planets (Bennett et al., 2012)>
- OGLE-2003-BLG-235L** first lensing planet (Bond et al., 2004)> HST identification (Bennett et al., 2006)> retrospective (Bond, 2012)>
- OGLE-2005-BLG-71L** second lensing planet, and first high-magnification event (Udalski et al., 2005)> HST astrometry and photometry (Dong et al., 2009b)>
- OGLE-2005-BLG-169L** extremely high-magnification event,  $A \sim 800$  (Gould et al., 2006b)> characterisation of the resonant caustic (Chung, 2009)> HST confirmation of proper motion (Bennett et al., 2015) >
- OGLE-2005-BLG-390L** low-mass planet (Beaulieu et al., 2006)> inferences on surface properties (Ehrenreich et al., 2006a)> limits on companions (Kubas et al., 2008)>
- OGLE-2006-BLG-109L** first two-planet lensing system, with orbital motion of the outer planet (Gaudi et al., 2008)> habitability (Malhotra & Minton, 2008)> formation and dynamical stability (Wang et al., 2009)> improved parameters and orbit analysis (Bennett et al., 2010)> terrestrial planet formation in inclined systems (Jin & Ji, 2011)> mean motion resonances and migration (Wang, 2011)> formation and habitability (Wang & Zhou, 2011)>

- OGLE-2007-BLG-349LAB** first circumbinary planet microlensing event,  $80M_{\oplus}$ , orbiting a pair of M dwarfs with masses  $0.4M_{\odot}$  and  $0.3M_{\odot}$  (Bennett et al., 2016)>
- OGLE-2007-BLG-368L** Neptune-mass planet, and frequency constraints beyond the snow line (Sumi et al., 2010)>
- OGLE-2008-BLG-92L** binary lens with circumprimary planet (Poleski et al., 2014a)>
- OGLE-2008-BLG-355L**  $4.6M_J$  planet at a projected 1.7 au from a low-mass star (Koshimoto et al., 2014)>
- OGLE-2011-BLG-251L** planet orbiting M dwarf host beyond the snow line (Kains et al., 2013)>
- OGLE-2011-BLG-265L**  $0.6M_J$  planet orbiting M dwarf host beyond the snow line, with prospects for future follow-up (Skowron et al., 2015)>
- OGLE-2012-BLG-26L** second two-planet system: two Jovian mass planets beyond the snow line (Han et al., 2013b)> revised host star flux and event model based on Keck and Subaru adaptive optics imaging (Beaulieu et al., 2016)>
- OGLE-2012-BLG-358L**  $1.9M_J$  planet orbiting a field brown dwarf (Han et al., 2013a)>
- OGLE-2012-BLG-406L**  $3.9M_J$  mass planet beyond the snow line (Poleski et al., 2014b)> re-analysis including parallax and lens orbital motion (Tsapras et al., 2014)>
- OGLE-2012-BLG-563L** Saturn-mass planet around an M dwarf; mass constrained by Subaru adaptive optics imaging (Fukui et al., 2015)>
- OGLE-2012-BLG-724L** short-duration event; Saturn-mass planet around an M dwarf (Hirao et al., 2016)>
- OGLE-2012-BLG-950L**  $35M_{\oplus}$  planet; long-term distortion in the MOA and OGLE light curve attributed to microlens parallax; planet mass estimated from parallax and high-resolution Keck AO flux (Koshimoto et al., 2017b)>
- OGLE-2013-BLG-102L** planet around low-magnification binary lens of  $0.1M_{\odot}$  and  $0.01M_{\odot}$  separated by 0.8 au (Jung et al., 2015)>
- OGLE-2013-BLG-132L** Saturn-mass planet orbiting an M-dwarf, covered with high cadence by OGLE and MOA (Mróz et al., 2017b)>
- OGLE-2013-BLG-341LB**  $2M_{\oplus}$  circumprimary planet, binary separation  $\sim 15$  au (Gould et al., 2014)>
- OGLE-2013-BLG-723L** not in NASA Exoplanet Archive; Venus-mass planet orbiting brown dwarf (Udalski et al., 2015a)> non-planetary interpretation (Han et al., 2016a)>
- OGLE-2013-BLG-1721L** Saturn-mass planet orbiting an M-dwarf, covered with high cadence by OGLE and MOA (Mróz et al., 2017b)>
- OGLE-2013-BLG-1761L** not in NASA Exoplanet Archive; suggested massive planet around an M/K dwarf; discovery (Hirao et al., 2017)>
- OGLE-2014-BLG-124L** planet in the near- to mid-disk, and microlens parallax from Spitzer (first space-based microlensing parallax) (Udalski et al., 2015b)> sensitivity analysis for simultaneous observations from space and ground (Zhu et al., 2015a)>
- OGLE-2014-BLG-676L** cold gas giant (Rattenbury et al., 2017)>
- OGLE-2014-BLG-1760L**  $0.5M_J$  planet, with high relative proper motion (Bhattacharya et al., 2016)>
- OGLE-2015-BLG-051L**  $\equiv$  KMT-2015-BLG-048;  $0.7M_J$  orbiting M dwarf (Han et al., 2016b)>
- OGLE-2015-BLG-954L**  $4M_J$  planet orbiting a relatively nearby (0.6 kpc) M dwarf; detected by 2 of the 3 KMTNet telescopes during commissioning (Shin et al., 2016)> MOA data covering the caustic exit, finite source effect and lens-source relative motion (Bennett et al., 2017)>
- OGLE-2015-BLG-966L** cold Neptune planet in the near- to mid-disk, and (second) microlens parallax from Spitzer (Street et al., 2016)>
- OGLE-2015-BLG-263L** discovered as a ‘repeating event’, in which the companion produced its own single-mass light curve after the event produced by the primary had ended (Han et al., 2017c)>
- OGLE-2016-BLG-596L** not in NASA Exoplanet Archive; high mass ratio planet from a high-magnification pure survey event; discovery (Mróz et al., 2017a)>
- OGLE-2015-BLG-613L** planetary companion to a binary lens, with separate resolution of lens and source expected around 2024; discovery (Han et al., 2017d)>
- OGLE-2016-BLG-1190L** borderline planet/brown dwarf object ( $13.4M_J$ ), probably in the Galactic bulge/bar; dense survey coverage from OGLE, MOA, KMTNet, with K2 campaign 9 data; discovery (Ryu et al., 2018)>
- OGLE-2016-BLG-1195L** lowest mass planet found by microlensing; planet orbits an ultracool dwarf (Bond et al., 2017b)> KMTNet with Spitzer yield  $M_p = 1.4 \pm 0.3M_{\oplus}$  (Shvartzvald et al., 2017b)>
- OGLE-2017-BLG-173L** low mass ratio planet, with event arising from a (large) bright source passing over and enveloping the planetary caustic, termed a ‘Hollywood’ event; discovery (Hwang et al., 2018b)>
- In NASA Exoplanet Archive, or reported, after 2018-01-01:
- OGLE-2016-BLG-1190** candidate free-floating planet of Neptune mass, with mass constrained by the event’s ultra-short duration ( $t_E = 0.320 \pm 0.003$  d), combined with a measured angular Einstein ring size (Mróz et al., 2018)>
- UKIRT-2017-BLG-001L** infrared high-extinction event in the Galactic bulge; discovery (Shvartzvald et al., 2018)>

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# Appendix F. Imaging exoplanets

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This appendix includes objects appearing in the online NASA Exoplanet Archive as of 31 December 2017.

These notes list some key attributes of the system to underline its particular interest, give some indication of the attention the object has received (through the length of the bibliography), and provide a concise note on each paper to serve as a guide to the literature and a narrative of the progress in understanding the system. It makes no claim for completeness, and CDS–SIMBAD should be consulted for more details.

It includes only cross-identifications which are relevant in context, e.g., as used in the early discovery literature. CDS–SIMBAD or the NASA Exoplanet Archive should be consulted for other aliases. If a different alias was used in the NASA archive, this is explicitly noted.

The electronic version includes three classes of hyperlink: the object identifier (in bold) is linked to the host star page of the NASA Exoplanet Archive (it will be invalid if their syntax changes); each citation is linked to the bibliography; and the > icon following the citation links to the relevant ADS page.

Ordering is by object name and, for Bayer–Flamsteed designations, by constellation.

## Notes on individual systems

### Star names

**Fomalhaut** nearby (7.7 pc) star with cold dust disk; object predicted from disk morphology; observations over 1.73 yr show orbital motion; planetary nature continues to be debated as a consequence of the eccentric disk structure, and non-detection in the infrared; dust clumps in the debris disk (Wyatt & Dent, 2002)> sub-mm observations of an asymmetric disk (Holland et al., 2003)> debris disk observed with Spitzer (Stapelfeldt et al., 2004)> planetary system proposed to explain the debris disk structure (Kalas et al., 2005)> predictions for a planet lying just inside the eccentric ring (Quillen, 2006a)> planet detected with HST–ACS (Kalas et al., 2008)> interferometric detection of hot dust with VLT–VINCI (Absil et al., 2009)> constraints on planet mass from disk morphology (Chiang et al., 2009)> long-range outward migration (Crida et al., 2009b)> possible formation by gravitational instability (Dodson-Robinson et al., 2009)> spin-orbit alignment from optical long baseline interferometry (Le Bouquin et al., 2009)> Spitzer–IRAC limits on planetary companions (Marengo et al., 2009)> planet formation constraints from gravitational instability (Nero & Bjorkman, 2009)> collisional modeling in dusty debris disks (Stark & Kuchner, 2009)> lunar phase of dust grains (Min et al., 2010)> imaging limits from VLT–PIONIER (Absil et al., 2011b)> possible formation by gravitational instability (Boss, 2011b)> Herschel images indicating an extrasolar Kuiper belt at the height of its dynamical activity (Acke et al., 2012)> high-resolution ALMA observations (Boley et al., 2012a)> Subaru–IRCS and archival HST–ACS characterisation (Currie et al., 2012a)> non-detection in the infrared (Janson et al., 2012b)> age and binarity of host star (Mamajek, 2012)> constraints on collisional models of

planetesimals debris disk from 7 mm emission (Ricci et al., 2012a)> Keck–NIRC2 search for thermal emission from planetary companions (Currie et al., 2013b)> independent analysis of HST archival data (Galicher et al., 2013)> VLT–NACO coronagraphic observations (Kenworthy et al., 2013)> HST–STIS coronagraphic imaging (Kalas et al., 2013)> interferometric study with VLT–VINCI (Lebreton et al., 2013)> hydrodynamical models can replicate sharp eccentric rings in debris disk without invoking planets (Lyra & Kuchner, 2013)> Fomalhaut C (Mamajek et al., 2013)> Keck null-interferometry (Mennesson et al., 2013)> asteroid belts (Su et al., 2013)> planet orbit and dynamical effects on outer dust belt (Beust et al., 2014)> models of impacts, captures, and collisional cascades to account for the bright dust cloud (Kenyon et al., 2014)> discovery of Fomalhaut C debris disk (Kennedy et al., 2014b)> coronagraphic imaging analysis (Meshkat et al., 2014)> dynamical consequences of the planet’s orbit (Tamayo, 2014)> constraints on gas content (Cataldi et al., 2015)> dynamical history (Faramaz et al., 2015)> high-contrast Spitzer imaging (Janson et al., 2015)> collisional cascade models (Kenyon & Bromley, 2015a)> interpretation as dust cloud produced by disk planetesimal collisions (Lawler et al., 2015)> upper limits to the CO mass (Matrà et al., 2015)> explanation as a background neutron star (Neuhäuser et al., 2015)> gap clearing by planets (Nesvold & Kuchner, 2015b)> orbital fitting of imaged planetary companions with high eccentricities and unbound orbits (Beust et al., 2016)> detection limits for debris disks using VLT sparse aperture masking (Gauchet et al., 2016)> apocentre glow in eccentric debris disks (Pan et al., 2016)> inner debris disk structure from ALMA (Su et al., 2016)> ALMA 1.3 mm observations of the dust emission from the complete outer debris disk (MacGregor et al., 2017a)> ALMA CO J = 2–1 emission from the cometary belt (Matrà et al., 2017b)> foreground neutron star hypothesis constrained by Chandra X-ray limits (Poppenhaeger et al., 2017)> 1.3 mm ALMA observations of the debris disk (White et al., 2017)> gap clearing by planet’s sweeping secular resonance (Zheng et al., 2017)> ‘Cooper pair’ modeling of the stellar triple system (Feng & Jones, 2018b)> dust belt structure modeled with the inclusion of nearby stellar companions (Kaib et al., 2018)>

### Constellation identifiers

- κ **And** super-Jupiter around late B-type star, from Subaru–HiCIAO SEEDS (Carson et al., 2013)> confirmed from common proper motion;  $\Delta\theta = 1.1$  arcsec; constraints on the companion mass, system age, and further multiplicity (Hinkley et al., 2013)> characterisation from high-contrast Keck and LBTI observations (Bonfey et al., 2014a)> age of host star from interferometry (Jones et al., 2016a)> H<sub>2</sub>O abundance from infrared spectroscopy (Todorov et al., 2016)>
- CT Cha** common proper motion companion confirmed by VLT–NACO from T Tauri survey in the Chamaeleon star-forming region (Schmidt et al., 2008)> observations with VLT–NACO (Schmidt et al., 2009)>
- 51 Eri** young Jovian planet detected with Gemini–GPI (Macintosh et al., 2015)> astrometric confirmation and preliminary orbital parameters from GPI (De Rosa et al., 2015)> combined imaging, astrometry and radial velocity constraints (Montet et al., 2015a)> atmospheric convection, quenching, and derived composition (Moses et al., 2016)> photolytic hazes in the atmosphere (Zahnle et al., 2016)> fast orbit computation (Blunt et al., 2017)> 1–5 μm Gemini–GPI spectrophotometry favours cold-start core accretion with core mass 15–127 M<sub>⊕</sub> (Rajan et al., 2017)> spectral and atmospheric characterisation with VLT–SPHERE (Samland et al., 2017)>
- GQ Lup** common proper motion companion confirmed by VLT–NACO

- from T Tauri survey in the Lupus star-forming region (Neuhäuser et al., 2005) >  $\Delta\theta = 0.7$  arcsec,  $\Delta m = 6$  mag comoving confirmation from VLT-NACO (Guenther et al., 2005) > visible and near-infrared photometry (Marois et al., 2007) > high-contrast characterisation from Keck-OSIRIS integral field spectroscopy (McElwain et al., 2007) > near-infrared integral-field spectroscopy (Seifahrt et al., 2007) > astrometric and photometric monitoring (Neuhäuser et al., 2008) > mm dust emission (Dai et al., 2010a) > Herschel-PACS spectroscopy suggesting crystalline H<sub>2</sub>O-ice and silicates (McClure et al., 2012) > astrometric follow-up with VLT-NACO and HST (Ginski et al., 2014) > slow spin and orbital configuration (Schwarz et al., 2016a) > limits on circumplanetary disk from ALMA CO observations (MacGregor et al., 2017b) > confirmation from Subaru-SEEDS (Uyama et al., 2017a) > disk structure from ALMA and MagAO (Wu et al., 2017) >
- HN Peg T** dwarf companion detected in a survey of nearby stars using Spitzer-IRAC (Luhman et al., 2007b) >
- AB Pic** companion of planet/brown dwarf mass from deep imaging of young (L dwarf) member of Tucana-Horologium with VLT-NACO (Chauvin et al., 2005b) >  $\Delta\theta = 5.5$  arcsec; near-infrared integral-field spectroscopy with VLT-SINFONI (Bonnefoy et al., 2010) >
- $\beta$  Pic** planet in  $\sim 20$ -yr orbit at 8–15 au; only a selection of the papers published before the planet confirmation in 2009 are included here: discovery of the circumstellar disk (Smith & Terrile, 1984) > comet-like bodies in the protoplanetary disk (Beust et al., 1994) > planet on inclined orbit can explain the warped debris disk (Mouillet et al., 1997) > rings in the planetesimal disk (Kalas et al., 2000) > inner disk rings (Wahhaj et al., 2003) > early extrasolar planetary system revealed by planetesimal belts (Okamoto et al., 2004) > evidence for comet-like bodies (Roberge et al., 2006b) > evidence for planets (Freistetter et al., 2007) > planet detected from imaging of the dusty disk using VLT-NACO (Lagrange et al., 2009b) > dust distribution (Ahmic et al., 2009) > fine structure from VLT-NACO (Boccaletti et al., 2009) > orbital constraints from Keck AO (Fitzgerald et al., 2009) > planetary transit explanation for the photometric variations observed in November 1981 (Lecavelier des Etangs & Vidal-Madjar, 2009) > deep imaging and orbit constraints (Lagrange et al., 2009c) > deep near-infrared interferometric search for low-mass companions (Absil et al., 2010) > detectability assessment with GPI (Kataria & Simon, 2010) > confirmation from high-contrast high-spatial resolution near-infrared images with VLT-NACO (Lagrange et al., 2010a) > 4  $\mu$ m imaging from VLT-NACO apodising phase plate (Quanz et al., 2010b) > high angular resolution detection at 2.2  $\mu$ m with VLT-NACO (Bonnefoy et al., 2011) > gas-braking (Brandeker, 2011) > 5  $\mu$ m imaging and evidence for a misalignment between the planet and the warped inner disk (Currie et al., 2011b) > misalignment and the warped inner disk (Dawson et al., 2011) > ro-vibrational CO detection (Troutman et al., 2011) > 1.3-mm imaging with the Submillimeter Array (Wilner et al., 2011) > orbit characterisation (Chauvin et al., 2012b) > hot circumstellar material imaged with VLT-PIONIER (De frère et al., 2012) > planet constraints from HARPS (Lagrange et al., 2012b) > planet position with respect to the debris disk (Lagrange et al., 2012a) > mineralogy and structure of the inner debris disk (Li et al., 2012b) > VLT imaging of the gas disk (Nilsson et al., 2012) > background galaxy (Regibo et al., 2012) > companion searches to 2 au with VLT-NACO (Absil et al., 2013b) > independent imaging confirmation with Gemini-NICI (Boccaletti et al., 2013) > near-infrared energy distribution (Bonnefoy et al., 2013) > VLT-Gemini atmospheric study (Currie et al., 2013a) > unusual gas composition in the disk (Xie et al., 2013) > physical and orbital properties (Bonnefoy et al., 2014b) > disk asymmetry attributed to giant impacts (Jackson et al., 2014) > shape, internal structure and gravity (Kong et al., 2014) > two families of exocomets (Kiefer et al., 2014b) > deep imaging of the innermost disk (Milli et al., 2014) > Magellan AO observations (Males et al., 2014) > orbit from Gemini-NICI (Nielsen et al., 2014) > rotational broadening of 25 km s<sup>-1</sup> indicates rapid planetary spin rate (Snellen et al., 2014) > atmospheric model from SPHERE observations (Baudino et al., 2015) > H-band spectrum (Chilcote et al., 2015) > inner disk in polarised light (Millar-Blanchaer et al., 2015) > Magellan AO observations (Morzinski et al., 2015) > model of colliding planetesimals (Nesvold & Kuchner, 2015a) > gap clearing by planets (Nesvold & Kuchner, 2015b) > dust model based on imaging with HST-STIS, HST-WFC3, Spitzer-MIPS, Herschel-PACS, and ALMA (Ballering et al., 2016) > detection limits for debris disks using sparse aperture masking at the VLT (Gauchet et al., 2016) > self-consistent gas disk model (Kral et al., 2016) > planetary orbit (Lecavelier des Etangs & Vidal-Madjar, 2016) > orbit (the Hill sphere) transit prospects (Wang et al., 2016b) > exocomet circumstellar Fe I absorption (Welsh & Montgomery, 2016) > 1–2.4  $\mu$ m spectrum with GPI (Chilcote et al., 2017) > detection of [C I] emission with ALMA (Higuchi et al., 2017) > exocomet flux and CO/CO<sub>2</sub> ice abundance from ALMA CO observations (Matrà et al., 2017a) > 31  $\delta$  Scuti pulsation frequencies (28 new) from Antarctic ATSEP observations (Mékarnia et al., 2017) > bRing observatory dedicated to monitoring the Hill sphere transit (Stuik et al., 2017) > physical properties of the neutral Fe I gas from 1700 HARPS spectra from 2003–15 (Vidal-Madjar et al., 2017) > HI Ly- $\alpha$  detected in gas disk from HST-COS (Wilson et al., 2017) > exo-ring environment revealed by HST-STIS imaging (Schneider et al., 2018) >
- UG Psc** wide planetary-mass companion to a young M3 star, discovered from GMOS spectroscopy with Gemini-S; confirmed from CFT-WIRCam near-infrared imaging (Naud et al., 2014) > search for photometric variability with CFHT-WIRCam (Naud et al., 2017b) >
- DH Tau** discovered from near-infrared coronagraphic observations of the classical T Tauri star with Subaru-CIAO (Itoh et al., 2005) >  $\Delta\theta = 2.3$  arcsec; mid-infrared observations of the transition disk (Gräfe et al., 2011) > VLT-SINFONI spectroscopy (Patience et al., 2012) > astrometric follow-up with VLT-NACO and HST (Ginski et al., 2014) > planetary accretion rates (Zhou et al., 2014c) > limit on circumplanetary disk mask from IRAM-NOEMA (Wolff et al., 2017) >
- FU Tau** pair of young brown dwarfs in the Taurus star-forming region discovered from Spitzer-IRAC (Luhman et al., 2009) >  $\Delta\theta = 5.7$  arcsec; molecular outflow (Monin et al., 2013) >

### Main catalogues

- GJ 504** cold Jovian planet around Sun-like star from Subaru-HiCIAO imaging (Kuzuhara et al., 2013) > direct imaging detection of CH<sub>4</sub> with Subaru-HiCIAO (Janson et al., 2013a) > spectral energy distribution models from LBT-LEECH observations (Skemer et al., 2016) > estimated lightning flash densities (Hodosán et al., 2016a) > chemical composition and age of 2.5 Gyr (D’Orazi et al., 2017) >
- HD 95086** 4–5 Jupiter-mass planet discovered from direct imaging with VLT-NACO (Rameau et al., 2013c) > confirmation from Gemini-NICI H-band observations (Meshkat et al., 2013) > confirmation by direct imaging with VLT-NACO (Rameau et al., 2013b) > detection and characterisation with Gemini-GPI (Galicher et al., 2014) > debris distribution and constraints on multi-planet architectures (Su et al., 2015) > 1.5–2.2  $\mu$ m spectral characterisation from GPI (De Rosa et al., 2016) > disk geometry from astrometric monitoring with GPI 2013–16 (Rameau et al., 2016) > broad disk with sharp boundaries from ALMA 1.3 mm observations (Su et al., 2017b) >
- HD 100546** giant planet at 50 au around Herbig Ae/Be star discovered from direct imaging with VLT-NACO (Quanz et al., 2015a) > earlier observations of disk structure and evidence for planets: evidence for star-grazing comets or planetesimals from IUE (Grady et al., 1997) > resolved circumstellar disk in the thermal infrared (Liu et al., 2003b) > disk imaged at 3.4 mm (Wilner et al., 2003) > inner disk cavity with evidence for young planetary system (Grady et al., 2005) > resolving disk rotation, and evidence for a giant planet (Acke & van den Ancker, 2006) > inner disk structure (Benisty et al., 2010) > polarimetric differential imaging of the disk between 10–140 au with VLT-NACO (Quanz et al., 2011) > structure of the planet-forming region (Tatulli et al., 2011) > warm gas at 50 au (Goto et al., 2012) > young protoplanet candidate embedded in the disk (Quanz et al., 2013a) > multi-epoch scattered light observations (Avenhaus et al., 2014a) > near-infrared spectroscopy and further evidence for an orbiting companion (Brittain et al., 2014) > candidate detection with Gemini-NICI and additional (planet-induced) disk structure at small separations (Currie et al., 2014d) > asymmetric disk near the gap (Panić et al., 2014) > resolved imaging with ALMA (Pineda et al., 2014) > two companions suggested from ALMA (Walsh et al., 2014) > high-contrast imaging/integral field spectroscopy/polarimetry with Gemini-GPI, with evidence for multiple accreting planets (Currie et al., 2015) > evidence for sequential planet formation (Pinilla et al., 2015) > hydrodynamic simulations of circumplanetary disk (Perez et al., 2015) > 3.8–4.8  $\mu$ m observations with VLT-NACO (Quanz et al., 2015a) > morphology and evidence for very young planets (Quanz, 2015) > polarised light and infrared observations with VLT-SPHERE show high brightness contrasts and arm-like structures (Garufi et al., 2016) > shocks and spiral disk structures (Lyra et al., 2016) > scattered light

- mapping of the protoplanetary disk (Stolker et al., 2016)> confirmation of protoplanet candidate and second emission source at 13–14 au from Gemini–GPI (Currie et al., 2017)> complex spiral structure from Gemini–GPI and MagAO (Follette et al., 2017)> luminosity interpreted through models of planetary accretion shock (Marleau et al., 2017)> bar-like structure across the disk gap in H $\alpha$  polarised light with VLT–SPHERE/ZIMPOL (Mendigutía et al., 2017)> disk emission in H $\alpha$  from Gemini–GPI and MagAO (Rameau et al., 2017)> ALMA CO emission tracing warp or radial flow within 100 au (Walsh et al., 2017)>
- HD 106906** planetary-mass companion orbiting a tight stellar binary at 7 arcsec (650–700 au); discovered with the Magellan Adaptive Optics (MagAO) + Clio2 system (Bailey et al., 2014b)> asymmetric disk distribution from HST–ACS (Kalas et al., 2015)> narrow edge-on disk revealed by VLT–SPHERE (Lagrange et al., 2016)> disk structure from MagAO (Wu et al., 2016b)> 1.1–2.5  $\mu$ m spectroscopy with VLT–SINFONI yields mass of 11.9  $M_J$  (hot start) or 14.0  $M_J$  (cold start) (Daemgen et al., 2017a)> disk morphology from Lidov–Kozai perturbations from exterior companion (Nesvold et al., 2017)> wide orbit originating from inward migration and binary scattering (Rodet et al., 2017)>
- HD 131399A** not in NASA archive; young 4  $M_J$  planet in triple-star system, orbiting star A at 50–100 au; claimed discovery with VLT–SPHERE (Wagner et al., 2016)> low-mass stellar companion in a 10-d orbit (Lagrange et al., 2017)> dynamical stability (Funk et al., 2017)> formation of wide-orbit gas giants from inner-disk scattering and orbit circularisation (Higuchi & Ida, 2017)> evidence from Gemini–GPI, VLT–SPHERE, and Keck–NIRC2 that the suggested planet is a background star (Nielsen et al., 2017)> stellar parameters (Przybylla et al., 2017)> stability analysis and prospects for planet ejection (Veras et al., 2017b)>
- HD 203030** young substellar companion near the L/T transition discovered with Hale 5-m PHARO camera (Metchev & Hillenbrand, 2006)> astrometric follow-up with VLT–NACO and HST (Ginski et al., 2014)> low-gravity spectral features and revised age of HD 203030B (Miles-Pérez et al., 2017)>
- HD 206893B** not in NASA archive; discovery inside a debris disk by VLT–SPHERE (Milli et al., 2017a)> follow-up observations with VLT–SPHERE and others (Delorme et al., 2017)>
- HIP 65426**  $\Delta\theta = 0.8$  arcsec; discovered from the VLT–SPHERE SHINE programme (Chauvin et al., 2017)>
- HIP 78530**  $\Delta\theta = 4.5$  arcsec; discovered from imaging of the Upper Sco association with Gemini–N–NIRI (Lafrenière et al., 2011)> Gemini 0.9–2.45  $\mu$ m spectroscopy (Lachapelle et al., 2015)>
- HIP 79462** not in NASA archive; discovery with Subaru–SEEDS (Uyama et al., 2017a)>
- HR 2562** substellar companion to a nearby debris disk system, discovered from imaging with Gemini–GPI (Konopacky et al., 2016b)>
- HR 8799** 4-planet system; high-contrast imaging with Keck–NIRC2 and Gemini–NIRI revealed objects b,c,d (Marois et al., 2008b) > with an inner object (planet e) later evident from Keck imaging (Marois et al., 2010)> possible formation by gravitational instability (Dodson-Robinson et al., 2009)> H-band image from 2002 observations with Subaru–AO confirming counter-clockwise orbit (Fukagawa et al., 2009)> prospects for future planetary scattering (Goździewski & Migaszewski, 2009)> HST–NICMOS detection of planet b in 1998 (Lafrenière et al., 2009) > pre-discovery 2007 image with Keck–AO (Metchev et al., 2009)> formation by gravitational instability (Nero & Bjorkman, 2009)> system architecture (Reidemeister et al., 2009)> nature of the debris disk (Su et al., 2009)> near-infrared spectroscopy (Bowler et al., 2010b)> search for wide companions with Gemini and HST–NICMOS (Close & Males, 2010)> resonances, stability and masses (Fabrycky & Murray-Clay, 2010)> thermal infrared MMT–AO observations (Hinz et al., 2010)> metallicity of the massive protoplanets if formed by gravitational instability (Helled & Bodenheimer, 2010)> spatially-resolved spectroscopy (Janson et al., 2010)> planetesimal belts (Moro-Martín et al., 2010a)> possible brown dwarf nature of companions (Moro-Martín et al., 2010b)> dynamical simulations (Marshall et al., 2010)> age determination from asteroseismology (Moya et al., 2010a)>  $\lambda$  Boo nature of host star (Moya et al., 2010b)> image of a fourth planet from Keck (Marois et al., 2010)> astrometry with VLT–NACO (Bergfors et al., 2011)> atmospheric clouds and chemistry in planet b (Barman et al., 2011a)> possible formation by gravitational instability (Boss, 2011b)> Subaru–VLT–MMT study (Currie et al., 2011a)> M-band imaging (Galicher et al., 2011b)> constraints on companions inside 10 au (Hinkley et al., 2011a)> spatially-resolved sub-mm imaging of the debris disk (Hughes et al., 2011)> model atmospheres (Madhusudhan et al., 2011a)> spatially-resolved sub-mm imaging of the debris disk (Patience et al., 2011)> orbital motion from 1998 HST data, and constraints on inclination, eccentricity, stability (Soummer et al., 2011a)> determination of host star inclination from asteroseismology (Wright et al., 2011a)> CHARA array host star angular diameter favours planetary masses (Baines et al., 2012)> direct detection and orbital analysis from archival 2005 Keck–NIRC2 data (Currie et al., 2012b)> masses, radii and cloud properties (Marley et al., 2012)> shape of debris disk inner edge from chaotic zone (Mustill & Wyatt, 2012)> LBT adaptive optics imaging (Skemer et al., 2012)> constraints on orbit inclination and age (Sudol & Haghhighipour, 2012)> LBT observations and detection of planet e in H-band (Esposito et al., 2013)> detection of CO and H $_2$ O absorption (Konopacky et al., 2013)> effects of a planetesimal debris disk on system stability (Moore & Quillen, 2013)> near-infrared spectroscopy (Oppenheimer et al., 2013)> deep thermal infrared imaging and constraints on a fifth planet (Currie et al., 2014b)> possible double Laplace mean motion resonances, 1e:2d:4c:8b (Goździewski & Migaszewski, 2014)> Gemini–GPI spectroscopy of planets c and d (Ingraham et al., 2014)> atmospheric analysis (Lee et al., 2014d)> constraints on the initial entropy (Marleau & Cumming, 2014)> resolved imaging of the debris disk with Herschel (Matthews et al., 2014a)> LBT and Magellan adaptive optics imaging at 3–5  $\mu$ m (Skemer et al., 2014b)> detection of H $_2$ O, CH $_4$ , and CO with Keck–OSIRIS (Barman et al., 2015)> constraints on architecture (Maire et al., 2015)> astrometry and orbital motion (Pueyo et al., 2015)> high-cadence high-contrast imaging from VLT–SPHERE first-light (Aparicio et al., 2016)> physical and chemical properties from VLT–SPHERE first-light (Bonnefoy et al., 2016)> disk modeling from ALMA at 1.34 mm (Booth et al., 2016)> models of the inner debris disk (Contro et al., 2016)> long-term system stability (Göberg et al., 2016)> detection limits for debris disks using sparse aperture masking at the VLT (Gauchet et al., 2016)> limits on the debris disk from HST–STIS (Gerard et al., 2016)> astrometric constraints from Keck–NIRC2 (Konopacky et al., 2016a)> dynamical stability (Morrison & Kratter, 2016)> atmospheric convection, quenching, and derived composition (Moses et al., 2016)> spectrophotometry and astrometry from VLT–SPHERE first-light (Zurlo et al., 2016)> image processing using VIP with LBTI–LMIRCam and the vortex coronagraph (Gomez Gonzalez et al., 2017b)> atmospheric retrieval for the planets (Lavie et al., 2017b)> mas astrometry with VLT–SPHERE (Wertz et al., 2017)> spectroscopic modeling (Lavie et al., 2017b)> planetary migration as the origin of the 2:1 mean motion resonance (Ramos et al., 2017)> fifth planet’s effect on outer dust belt consistent with ALMA observations (Read et al., 2018)>
- 2M J0122–24** young dusty L dwarf companion at the deuterium-burning limit discovered with Keck–NIRC2 (Bowler et al., 2013)> long-slit spectroscopy from VLT–SPHERE (Hinkley et al., 2015)>
- 2M J0219–39** brown dwarf/planet-mass companion to a Tucana–Horologium M dwarf (Artigau et al., 2015)>
- 2M J0441+23** companion to young brown dwarf in Taurus star-forming region ( $\Delta\theta = 0.1$  arcsec) imaged with HST–WFPC2 and Gemini AO (Todorov et al., 2010b)>
- 2M J1207–39** young nearby brown dwarf companion in TW Hya association discovered from VLT–NACO imaging, 3 epochs over 1 year (Chauvin et al., 2004)> further VLT–NACO observations over 1 year (Chauvin et al., 2005a)> moving cluster distance (Mamajek, 2005)> emission-line variability (Scholz et al., 2005)> HST–NICMOS imaging (Song et al., 2006)> trigonometric parallax and luminosity determination (Billar & Close, 2007)> trigonometric parallax (Gizis et al., 2007)> temperature, mass, and evidence for edge-on disk (Mohanty et al., 2007)> underluminosity as a protoplanet collision aftermath (Mamajek & Meyer, 2007)> disk characterisation (Riaz & Gizis, 2007)> emission-line variability over hours to years (Stelzer et al., 2007)> high-resolution near-infrared spectrum (Patience et al., 2010)> cool, cloudy, CH $_4$  atmosphere from modeling (Barman et al., 2011b)> evidence against edge-on disk, and thick-cloud explanation for its underluminosity (Skemer et al., 2011)> Herschel–SPIRE observations (Riaz et al., 2012a)> LBT and Magellan adaptive optics imaging at 3–5  $\mu$ m (Skemer et al., 2014b)> rotational modulation from HST–WFC3 with a period 10.7 h (Zhou et al., 2016d)> angular rotation of the azimuthal asymmetry observed with HST–STIS attributed

to precession (Debes et al., 2017)> ALMA detection of compact disk (Ricci et al., 2017b)>

- 2M J2140+16** discovered from 3-yr of astrometry, spectroscopy, and Keck AO of low-mass field binaries (Konopacky et al., 2010)>
- 2M J2236+47** red planetary-mass companion to the AB Dor moving group candidate (Bowler et al., 2017b)>

#### Other

**CFBDSIR J1458** common proper motion companion discovered from Keck–NIRC2 AO imaging,  $\Delta\theta = 0.1$  arcsec (Liu et al., 2011b)>

**CHXR 73** discovered from imaging of the Chamaeleon I star-forming region using HST–ACS,  $\Delta\theta = 1.3$  arcsec (Luhman et al., 2006)>

**GSC 0621–00** discovered from Hale 5-m AO imaging survey for wide companions to solar-type stars in Upper Scorpius (Ireland et al., 2011)> circumplanetary accretion disk from Keck–OSIRIS (Bowler et al., 2011)> planetary accretion rates (Zhou et al., 2014c)> Gemini 0.9–2.45  $\mu\text{m}$  spectroscopy (Lachapelle et al., 2015)>

**LkCa 15** 2-planet system;  $\Delta\theta = 0.07, 0.10, 0.88$  arcsec; located inside a known gap in the protoplanetary disk of a solar analogue, revealed by non-redundant aperture masking interferometry at three epochs with LBT–LMIRCam (Sallum et al., 2015)> preceding and subsequent observations: structure of the protoplanetary disk (Piétu et al., 2007)> search for sub-stellar disk structure (Bonavita et al., 2010)> disk gap and indications of planet formation (Thalmann et al., 2010)> disk structure (Andrews et al., 2011a)> sulphur-bearing molecules in the protoplanetary disk (Dutrey et al., 2011)> nature of the transition disk (Isella et al., 2012)> direct-imaging evidence of a likely (proto)planet inside a known gap in the protoplanetary disk from Keck–NIRC2 (Kraus & Ireland, 2012)> disk searches (Isella et al., 2014)> disk structure from Gemini–NIRI (Thalmann et al., 2014b)> multiple companions on Keplerian orbits and accretion onto protoplanet b from LBT–LMIRCam (Sallum et al., 2015)> optical imaging polarimetry with VLT–SPHERE–ZIMPOL (Thalmann et al., 2015)> asymmetric disk structures in scattered light with VLT–SPHERE–IRDIS (Thalmann et al., 2016)> luminosity interpreted through models of planetary accretion shock (Marleau et al., 2017)> X-ray heating inferred from Chandra observations (Skinner & Güdel, 2017)>

**Oph 11** discovered from imaging of Ophiuchus star-forming clouds with Keck AO and Gemini–N–NIRI (Close et al., 2007)>

**Ross 458**  $\equiv$  DT Vir; discovered from spectroscopy with Magellan–FIRE (Burgasser et al., 2010b)> further observations (Birmingham et al., 2011)> effect of stellar wind on magnetosphere (Vidotto et al., 2014)>

**ROXs 12** discovery from Keck–NIRC2 (Kraus et al., 2014)> imaging search for close-in massive bodies responsible for outward scattering (Bryan et al., 2016a)> morphology and spin–orbit misalignment from Gemini–North–NIFS and Keck–OSIRIS (Bowler et al., 2017a)>

**ROXs 42B** companion near the deuterium-burning limit in a young binary star system discovered from various imaging and spectroscopy (Currie et al., 2014c)> independent observations with Keck–NIRC2 (Kraus et al., 2014)> spectroscopic confirmation (Bowler et al., 2014)> atmospheric modeling (Currie et al., 2014a)> high contrast imaging search for close-in massive bodies responsible for outward scattering (Bryan et al., 2016a)> mid-infrared characterisation from Keck–NIRC2 3–5  $\mu\text{m}$  photometry (Daemgen et al., 2017b)> confirmation from Subaru–SEEDS (Uyama et al., 2017a)>

**IRXs J1609–21** member of the Upper Scorpius association,  $\Delta\theta = 2.2$  arcsec; discovered from imaging and spectroscopy with Gemini–N–NIRI near-infrared AO (Lafrenière et al., 2008)> confirmation from astrometry with Gemini–ALTAIR (Lafrenière et al., 2010)> estimate of planet mass of  $14 \pm 2 M_J$  (Pecaut et al., 2012)> astrometric follow-up with VLT–NACO and HST (Ginski et al., 2014)> possible radio detection with GMRT (Sirothia et al., 2014)> Gemini 0.9–2.45  $\mu\text{m}$  spectroscopy (Lachapelle et al., 2015)>

**SR 12AB** discovered from near-infrared imaging and spectroscopy of a binary T Tauri star in the  $\rho$  Oph star-forming region with IRSF–SIRIUS,  $\Delta\theta = 8.7$  arcsec (Kuzuhara et al., 2011)> spectroscopic confirmation (Bowler et al., 2014)>

**USco CTIO 108** member of the Upper Sco association,  $\Delta\theta = 4.6$  arcsec; discovered from optical and near-infrared photometry and spectroscopy of a brown dwarf with WHT–ACAM (Béjar et al., 2008)> astrometric follow-up with VLT–NACO and HST (Ginski et al., 2014)>

**VHS J1256–12** brown dwarf triple system; discovered from imaging of a nearby M dwarf with ESA–VISTA–VIRCAM (Gauza et al., 2015)> thermal infrared imaging: clouds and equilibrium C chemistry (Rich et al., 2016)> Magellan adaptive optics imaging (Stone et al., 2016)>

**WD 0806–661B**  $\equiv$  GJ 3483; brown dwarf common proper motion companion to white dwarf primary, at  $\Delta\theta = 130$  arcsec; candidate for one of the coldest known brown dwarfs; discovered from multi-epoch Spitzer–IRAC imaging (Luhman et al., 2011)> age, mass and formation mechanism (Rodríguez et al., 2011)> confirmation from Spitzer–IRAC, VLT–HAWK–I, and Magellan–FourStar (Luhman et al., 2012)>

**WISEP J1217+16** wide companion to nearby brown dwarf discovered from imaging with Keck–NIRC2 (Liu et al., 2012)> resolved spectroscopy, age, and kinematics (Leggett et al., 2014)>



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