Exoplanets

Detection, Formation, Properties, Habitability

John W. Mason (Editor)

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Front cover illustrations: (Main image) A computer-generated simulation of a Jupiter-sized exoplanet shown crossing in front of the disk of its parent star. Image courtesy Jeffery Hall, Lowell Observatory. (Smaller image) Artist's concept of a planetary disk around a brown dwarf. Image courtesy NASA/JPL-Caltech/T.Pyle (SSC).

Back cover illustrations: (Top) Artist's impression of a Saturn-mass planet orbiting the sun-like star HD149026, with atmosphere based on models by James Cho. Image courtesy Greg Laughlin, University of California, Santa Cruz. (Bottom) Artist's impression of the Jupiter-sized planet discovered transiting a star 500 light-years from Earth. Image courtesy Jeffery Hall, Lowell Observatory.

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Editor's Preface

An extrasolar planet or exoplanet is a planet orbiting a star (or remnant of a star) beyond our Solar System. As of autumn 2007, about 250 exoplanets had been discovered around 220 different stars, including nearly two dozen multiple planet systems. No less than five exoplanets have been discovered orbiting the star 55 Cancri; one of the planets has nearly four times the mass of Jupiter, another is comparable with Jupiter in mass, two are slightly less massive than Saturn, while the innermost planet has a mass similar to that of Uranus.

Around 2300 years ago, the Greek philosopher Epicurius reflected on the existence of planets around other stars, and of life on those planets:

> *"There are infinite worlds both like and unlike this world of ours... We must believe that in all worlds there are living creatures and plants and other things we see in this world."*

And in the 16^{th} Century, the medieval scholar Giordano Bruno, in his work *De l'infinito, universo e mondi,* speculated:

> *"There are countless suns and countless Earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous. The countless worlds in the universe are no worse and no less inhabited than our Earth."*

Extrasolar planets became a subject of scientific investigation in the mid-19th Century, and although there were some unsubstantiated claims as to their discovery, it was not known how common they were, how similar they were to the planets of the Solar System, or indeed how typical the make up of our Solar System was in comparison with planetary systems around other stars. There was also the question of the habitability of such planets. Were there Earth-like planets orbiting other stars and, if so, could they have the necessary surface conditions to support some form of life?

What actually constitutes a planet? In February 2003, the Working Group on Extrasolar Planets (WGESP) of the International Astronomical Union produced a reasonable working definition of a "planet", agreeing to revise the definition as and when necessary, and as our knowledge improves. The WGESP considered that objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be ∼13 Jupiter masses (∼13 M_J) for objects of solar metallicity) that orbit stars or stellar remnants are "planets", no matter how they formed. As it happens, this deuterium-burning limit at ∼13 M_J resides near the upper-end of the observed exoplanet mass distribution.

The WGESP also decided that the minimum mass/size required for an extrasolar object to be considered a "planet" should be the same as that used in our Solar System. Here, of course, there has been very considerable deliberation and debate arising out of the resolutions passed at the IAU General Assembly in Prague in August 2006, mainly in relation to the status of "dwarf" bodies such as Pluto, Eris and Ceres within our own Solar System. As far as detected exoplanets are concerned, the minimum mass object detected to date is the 0.00007 M_J object (40 per cent the mass of Mercury) orbiting the pulsar PSR 1257+12, but the lowest mass companions to ordinary stars which have been discovered to date are Gl 876 d, which has a minimum mass of 0.0185 M_J (about 5.9 Earth masses), OGLE-05-390L b, which has an estimated mass of 0.017 M_J (about 5.4 Earth masses) and Gl 581 c, which has a minimum mass of 0.0158 M_J (about 5 Earth masses).

The WGESP also decided that 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. Furthermore, 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).

The first confirmed detections of exoplanets were made in early 1992, by the radio astronomers Aleksander Wolszczan and Dale Frail, but rather surprisingly these were not found around an ordinary star, but a pulsar – the superdense remnant of a massive star that has exploded as a supernova. The first definitive detection of an exoplanet orbiting an ordinary main-sequence star came in October 1995 with the announcement, by Michel Mayor and Didier Queloz of the University of Geneva, of an exoplanet orbiting the star 51 Pegasi. This discovery ushered in the modern era of exoplanet discovery, and since 2000 about 20–30 exoplanets have been discovered every year, with the most detections, by far, during 2007.

New discoveries and significant developments in exoplanet research continue at a frenetic pace, and it is difficult to keep up with progress in this exciting field. This multi-author volume comprises a collection of eleven topical reviews, each presented as a separate chapter, and covering an important aspect of exoplanet studies. The contributions have been written by scientists at the forefront of research in the selected areas, in a style which, we hope, will be accessible not only to advanced undergraduate students and beginning graduate students, but also to professional astronomers working in the field.

Although the direct imaging of exoplanets is extremely difficult at the present time, a variety of indirect detection methods are available. In Chapter 1, Patrick Irwin provides an overview of exoplanet detection techniques. The most successful take advantage of the fact that a planet orbiting a distant star can make its presence known through small, regular variations in the radial velocity or position of its parent star. However, exoplanets are increasingly being detected by observing the minute decrease in the light of the host star if an exoplanet happens to pass in front of it (in transit), or through techniques such as gravitational microlensing. So many exoplanets have now been found that it is possible to consider the statistics of the mass and orbital parameter distributions, and Chapter 1 includes a collection of plots showing the exoplanet mass distribution, their orbital period and orbital radius distribution, distributions of mass and radius and of eccentricity and radius for known exoplanets, and the distribution of host star metallicity. Chapter 1 concludes with a discussion of selection effects for different exoplanet detection programmes, and a look ahead to planned transit surveys and the techniques being developed for direct optical detection.

In Chapter 2, Jian Ge takes a detailed look at the most successful method employed to date for exoplanet detection, that of Doppler planet surveys. Of the roughly 250 exoplanets discovered to date, over 90 per cent have been detected by single object Doppler techniques. This chapter outlines the theory of the two principal Doppler methods: one using high resolution cross dispersed echelle spectrographs (the echelle method) and the other using dispersed fixed-delay interferometers (the DFDI method). Both methods have been successfully used for detecting new exoplanets. The main results of Doppler planet surveys over the past decade are then summarised, together with early results in the development of new Doppler techniques, especially multiple object techniques. Chapter 2 presents the scientific motivation for the next generation large-scale multi-object Doppler planet surveys and possible new science which will be addressed. Past experience has shown that the ability to move from single-object to multi-object observations has facilitated large-scale astronomical surveys (e.g. the Sloan Digital Sky Survey), and has consistently led to dramatic new discoveries. It is anticipated that similar advances will result from multi-object Doppler planet surveys in the next decade.

Another important exoplanet detection technique, that of gravitational microlensing, is reviewed by David Bennett in Chapter 3. This method relies upon chance alignments between background source stars and foreground stars which may host planetary systems. The background source stars serve as light sources that are used to probe the gravitational field of the foreground stars and any planets that they might host. The author explains how the microlensing method is unique among exoplanet detection methods in a number of respects, particularly in its ability to find low-mass planets at separations of a few AU. The basic physics of the microlensing method is reviewed together with typical planetary microlensing events. The author shows how such microlensing events may be used to enable the measurement of planetary orbital parameters, and he reviews early observational results highlighting the exoplanets discovered by microlensing to date. Finally, the author demonstrates that a low-cost, space-based microlensing survey can provide a comprehensive statistical census of extrasolar planetary systems with sensitivity down to 0.1 Earth-masses at separations ranging from 0.5 AU to infinity.

As George Rieke explains in Chapter 4, exoplanets move within tenuous disks of dust (and early-on, gas) that are relatively easy to detect. The dust intercepts energy from the parent star more efficiently than a planet can, and thus scatters and reradiates energy in far larger amounts than a planet could. In the process, it imposes its own signatures on this output. We know of hundreds of planetary systems through observation of circumstellar disks of dust, and we can learn indirectly about them if we can read these signatures. The author discusses the formation and evolution of protoplanetary disks in the context of terrestrial planet formation. He shows that although there is a well-defined overall pattern of protoplanetary disk characteristics, there is a wide range of starting conditions, e.g. disk masses, along with some variation in evolutionary timescales. Such differences presumably translate into a wide range of properties for the planetary systems that develop within these disks. The process of terrestrial planet formation continues well beyond the protoplanetary stage, and produces disks of debris from the planetesimal collisions. The observed behaviour of these debris disks can test many hypotheses regarding the evolution of the Solar System. Debris disks also enable astronomers to probe many different examples of how planetary systems evolve, since there are ~150 known examples within 50pc.

The interesting connection between brown dwarfs and exoplanets is explored by I. Neill Reid and Stanimir Metchev in Chapter 5. Brown dwarfs form like ordinary stars but, with masses below 0.075 solar masses, or 1.5×10^{29} kg, they fail to ignite core hydrogen fusion. Lacking a central energy source, they cool and fade on timescales that are rapid by astronomical standards. Consequently, the observed characteristics of old, cold brown dwarfs provide insight into the expected properties of gas-giant exoplanets. The chapter focusses on brown dwarfs as companions to main-sequence and evolved stars. Following a brief introduction to the intrinsic properties of brown dwarfs, including their observed characteristics and classification, the authors examine the different observational techniques used to identify very low mass companions of stars and review the advantages and challenges associated with each method. The authors summarise the results of various observational programs, particularly those regarding companion frequency as a function of mass and separation, and discuss the so-called 'brown dwarf desert'. The implications of these results for brown dwarf and planetary formation mechanisms are considered. The chapter concludes with a discussion of future surveys for low mass companions, particularly direct imaging programs that will have sufficient sensitivity to detect objects of planetary mass.

The detection of the first exoplanet around the G2V star 51 Pegasi in 1995 was a landmark discovery. The presence of this Jupiter mass planet in a very close 4.2-day orbit around the host star was quickly confirmed, and corroborated by Doppler evidence for more of these close-orbiting Jupiter mass planets (dubbed 'hot Jupiters') around a number of other nearby stars. Developments in experimental capabilities have meant that so called 'hot Saturns' and 'hot Neptunes' have also been discovered, and these close-orbiting planetary systems are discussed in detail by Hugh Jones, James Jenkins and John Barnes in Chapter 6. As the authors explain, although 51 Pegasi-like objects dominated early discoveries, other types of planets are considerably more common. The 51 Pegasi class were found first because they were the easiest to detect by the radial velocity method. In addition to being favoured by radial velocity surveys, the bias is even stronger in transit surveys. All known transiting exoplanets have periods less than a week. Although our overall knowledge of exoplanets has been fuelled by the growth in the sheer number and also by the broad range of parameter space now populated, close-orbiting planets characterised with a combination of precise radial velocity measurements and transit photometry have played a key role. In these close-orbiting systems it is possible to determine the mass and radius of the planet, which in turn yields constraints on its physical structure and bulk composition. The transiting geometry also permits the study of the planetary atmosphere without the need to spatially isolate the light from the planet from that of the star. This technique (known as transit spectroscopy or occultation spectroscopy) has enabled photometric and spectroscopic measurements of exoplanets to be made. As the authors of Chapter 6 make clear, the wide range of properties of close-orbiting planets has stimulated a plethora of physical models to explain their properties. They provide the sharpest test for theories of formation, e.g., gravitational instability versus core-accretion, the role of stellar metallicity in determining planetary core mass and how an irradiating star influences planetary contraction and migration, e.g., type I, type II and delayed migration. With the continuous development of experimental techniques, close-orbiting terrestrial-mass exoplanets are the exciting new frontier in astrophysics and will test a wide range of theoretical predictions.

The dynamical properties of multiple planet systems are reviewed by Rory Barnes in Chapter 7. As the author explains, the study of exoplanet dynamics is severely hampered by observational uncertainties. Although the detections themselves are robust, the orbital elements have significant uncertainties. The most problematic aspect of the Doppler technique is the mass-inclination degeneracy. If the inclination, the angle between the plane of the orbit and a reference plane, can be determined by a complementary method, such as astrometry or transits, this degeneracy may be broken, and the planetary masses and full three dimensional orbits identified. The mass-inclination degeneracy therefore makes many simulations, analyses, and hypotheses unreliable. Generally, in the dynamical studies discussed in Chapter 6, the masses are assumed to be the "minimum mass" – the mass if the orbit was exactly edge-on. Statistically, this choice is expected to be reasonably accurate. The Doppler technique also limits the ranges of planetary masses and orbital radii that may be observed, and so the observed planets may not be all the planets in a system. Consequently, the conclusions presented in Chapter 6 are subject to revision as additional planets may exist in each system that are either low-mass or orbit at large distances, and these unseen companions may significantly alter the best-fit orbits of the known planets. The author describes how the orbits of planets evolve due to tidal, resonant, and/or secular (long-term) effects. Basic analytical and numerical techniques can describe these interactions, and the author reviews orbital theory and analytical methods (secular theory and resonant interactions), and shows how N-body integrations are used to determine the evolution of a system. Multiple planet systems may also evolve chaotically, and some principles of chaos theory are described. Finally, the author discusses the current distributions of dynamical properties of known multiple exoplanetary systems, possible origins of these distributions, and compares exoplanetary systems with the Solar System.

There is increasing evidence that planets are ubiquitous, and may form around stars over a wide range in stellar masses. After a star dies, the planets may remain, and in some circumstances there may be a new epoch of planet formation after the main sequence. In Chapter 8, Steinn Sigurdsson discusses scenarios for the retention and formation of planets after the death of the parent star, and the prospects for detection, including current known post-main sequence systems. Planets in the so-called 'stellar graveyard' are, in many cases, easier observational targets than planets around main sequence stars, and different detection techniques may also be brought to bear, in some cases with much higher sensitivity, allowing the detection of low mass planets. This is particularly true in the case of the three exoplanets detected around the millisecond pulsar PSR 1257+12, which at 0.00007, 0.13 and 0.12 Jupiter masses are the lowest mass exoplanets discovered to date. The author discusses theories as to the origin of planets around pulsars, including the pulsar planet in the globular cluster Messier 4, before turning his attention to the detection of planets around white dwarfs. He also describes the recent exciting discovery of a giant planet around the extreme horizontal branch star V391 Pegasi. This is a well known pulsating subdwarf, a star that has terminated core hydrogen fusion on the stellar main sequence and evolved through a red giant branch phase. The planet must originally have been closer to the star, but moved outwards as the star lost mass, avoiding being swallowed by the red giant envelope as the star expanded. As the author explains, planets detected in the stellar graveyard reflect the 'live' population of planets, and in some cases provide potentially strong constraints on planet formation processes, and the general planet population.

A survey of currently known planet-hosting stars indicates that approximately 25 per cent of extrasolar planetary systems are within dual-star environments. Several of these systems contain stellar companions on moderately close orbits, and the existence of exoplanets in such binary systems has confronted dynamicists with many new challenges, as Nader Haghighipour explains in Chapter 9. Questions such as how are these planets formed, whether binary-planetary systems host terrestrial and/or habitable planets, how habitable planets form in such dynamically complex environments, and how such planets acquire the ingredients necessary for life, are among major topics of research in this area. Chapter 9 begins with a review of the dynamics of a planet in a binary star system, and in particular whether the orbit of a planet around its host star would be stable. The author then examines the formation of planets in binary star systems. In spite of the observational evidence that indicates the majority of main and pre-main sequence stars are formed in binaries or clusters, and in spite of the detection of potentially planet-forming environments in and around binary stars, planet formation theories are still unclear in explaining how planets may form in multi-star environments. The author then discusses the formation of giant and terrestrial planets in moderately close binary-planetary systems, and reviews the current status of planet formation theories in this area. The habitability of a binary system is then examined. Models of habitable planet formation in and around binary systems are presented, and their connections to models of terrestrial planet formation and water-delivery around single stars are discussed. Chapter 9 ends with a discussion of the future prospects for research in the field of planets in binary star systems.

The theme of the habitability of planets and the search for life beyond the Solar System is explored in detail by Victoria Meadows in Chapter 10. In its most conservative definition, a 'habitable world' is a solid-surfaced world, either a planet or moon, which can maintain liquid water on its surface. This definition is based on the fact that water is the one common constituent used by an enormous array of life forms on the Earth. Life may also be present in the atmospheres of planets, or in subsurface water tables or oceans, even in our own Solar System. However, as the author explains, when searching for life beyond our Solar System, we adopt the more conservative definition of the presence of surface water, because this definition also has the advantage of describing worlds that would be more detectable as habitable, even over enormous distances. After introducing the concept of habitable zones around stars which may harbour planets, the author explains how even a conservative definition of habitability still encompasses a vast array of potential worlds that could be considered habitable, without being similar to the present-day Earth. The techniques and space missions which will enable the direct detection of Earth-sized planets are then described, and aspects of the remote detection of planetary characteristics are outlined. Although characterising a planet for the ability to support life is an exciting first step, it is a precursor to the search for any indications that the planet already harbours life. Such signs of life, either past or present, when inferred from very distant measurements are called 'remote-sensing biosignatures'. As the author carefully explains, the search for these is based on the premise that widespread life will modify the atmosphere and surface of its planet, and that such modifications will be detectable on a global scale. The chapter concludes with a look at how such biosignatures might be detected.

There is good reason to hypothesise that giant exoplanets will be attended by significant moon systems. Moon systems exhibit diverse characteristics, and present unique environments – possibly even suitable habitats for life. As Caleb Scharf outlines in the final chapter, Chapter 11, such exomoons may share many characteristics with those in our own Solar System, as well as represent alternatives - possibly including temperate Mars- or Earth-sized bodies. In our own Solar System the majority of giant planet moons harbour substantial water ice mantles. The inferred internal structure and observed activity of many suggests the potential for extensive subsurface liquid water, both currently and in the past. A well known example of this is Jupiter's icy moon, Europa. Liquid water is vital for all forms of terrestrial life, through its integrated roles in biochemistry and geophysics. By contrast, the thick atmosphere and rich, low-temperature, hydrocarbon chemistry of Saturn's largest moon, Titan, points towards a highly complex surface environment paralleling some of the conditions on the early Earth, and conceivably offering alternative pathways for complex phenomena such as life. As the author concludes, detecting the presence of moons in exoplanetary systems is rapidly approaching feasibility, and will open a new window on such objects and their potential habitability.

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1 Detection Methods and Properties of Known Exoplanets

Patrick G. J. Irwin

Summary. Following the historic discovery of the first extrasolar planet, 51 Pegasi b, in 1995 (Mayor and Queloz, 1995) more than 200 planets orbiting other stars have now been catalogued. The vast majority of these planets have been detected with the radial velocity technique, which is biased towards heavy, close-orbiting planets. However, the number of lighter, more distantly orbiting known exoplanets is increasing steadily and, in addition, a growing fraction of exoplanets have now been discovered using other detection methods that may be more successful in detecting terrestrial-type planets. In this chapter we will review the main physical properties of the exoplanets (and their parent stars) discovered to date (28 February 2007) and will review the expectations of forthcoming observations.

1.1 Introduction

The question of just how unique our Solar System is has intrigued philosophers and scientists for centuries. While it has generally been assumed that there are almost certainly other planets orbiting other stars, it was not until the historic discovery of 51 Pegasi b in 1995 by Mayor and Queloz (1995) that the first conclusive proof of the non-uniqueness of the Solar System was obtained. The planet that was discovered though, and most of those discovered since with the same radial velocity technique (Sect. 1.2.1), is very different from the planets of our Solar System. 51 Peg b (the exoplanetary naming convention is to list the star name followed by 'b', 'c' ... in order of the planet's discovery) has a mass greater than or equal to 0.46 M_J, (where M_J is the mass of Jupiter) and orbits at a distance of only 0.05 AU in a period of just 4.2 days! The surface temperature of the planet, so close to its star, is calculated to be enormous ($\sim$ 1400 K) and the planet has been dubbed a 'hot Jupiter'.

1.2 Detection of Extrasolar Planets

Directly observing extrasolar planets is extremely difficult given the large brightness contrast between a star and its planets and also the small angular separation. For example, if our own Solar System were observed at a distance of, say, 5 parsecs, the greatest angular separation of the Sun and Jupiter would be just 1 arcsecond with the Sun appearing 10^9 times brighter at visible wavelengths. Under these conditions it would be impossible to pick Jupiter out from the Sun's glare (Lewis, 2004). One possible solution to this problem is to search for planets around dimmer stars such as white and brown dwarfs. Searches for extrasolar planets around white dwarfs have so far been unsuccessful (e.g. Burleigh et al., 2003; Friedrich et al., 2006), but four planets/brown dwarfs (Sect. 1.4.2) have now been directly imaged about brown dwarfs, the first being imaged by the Very Large Telescope (VLT) orbiting a brown dwarf, situated 200 light years away, at a distance of ~ 60 AU (Chauvin et al., 2005a). Another strategy is to attempt to detect the planet at wavelengths near the peak of the planet's Planck function. Observing at 50 μm rather than 0.6 μm reduces the flux ratio to 10^4 for the Sun-Jupiter system, but at these longer wavelengths the diffraction-limited angular resolution of any achievable telescope would be insufficient.

Although direct optical detection of extrasolar planets initially appeared very difficult, it was realised that it might be possible to indirectly detect them through their influence on the motion of the central star. There are two ways of doing this: 1) by observing the *radial velocity* of the star as the planetary system rotates about its centre-of-mass and 2) by observing the actual reflex motion[1] of the star against the heavens (*astrometry*). In addition, it also came to be realised that there was a chance that an extrasolar planet could be detected if it transited in front of its star, while other detection methods, such as gravitational lensing, revealed themselves serendipitously. There are now numerous methods of detecting extrasolar planets, which will be briefly summarised.

1.2.1 Radial Velocity Detections

For a planet of mass M_p in a circular orbit of radius a about a star of mass M_*, the star and planet will both orbit about their centre-of-mass, situated at a distance $2aM_p/\left(M_p + M_*\right)$ from the star. Equating the gravitational force with the centripetal force acting on the star, and assuming that $M_* \gg M_p$, the maximum velocity of the star v in the line of sight of an observer may be shown to satisfy $v^2 = G\left(M_p \sin i\right)^2/2M_*a$, where i is the inclination of the planet's orbit with respect to the observer, i.e. the angle between the normal to the orbital plane of the planet and the line from the star to the observer on the Earth. The radial velocity method can determine both $M_p \sin i$ and also, from the shape of the variation of v with time, the eccentricity, e, of the planet's orbit. It is worth noting that unless the inclination can be determined from other methods such as astrometry (Sect. 1.2.2), this method only provides a lower limit on the planet's mass. The technique is most effective for larger mass planets orbiting close to the lower mass stars (i.e. G and K type) since this gives the largest line-of-sight stellar velocity and it is crucial to

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[1] The reflex motion of the star is caused by both it and the planet orbiting their common centre of mass.

be able to distinguish the radial velocity of the star due to the orbit of a planet from the naturally occurring turbulent velocities present in a stellar photosphere. An example of a measured radial velocity curve for the star GJ 446 (Butler et al., 2004) is given in Fig. 1.1.

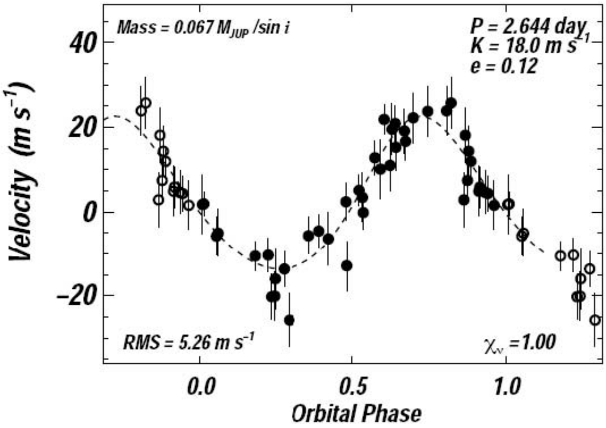

Fig. 1.1. Measured velocities vs orbital phase for GJ 436 (Butler et al., 2004). The dotted line is the radial velocity curve from the best-fit solution: $P = 2.644$ days, $e = 0.12$, $M \sin i = 0.067 M_J$

Since the discovery of 51 Peg b there have been detections (almost all by the radial velocity technique) of over 200 extrasolar planets. Indeed it is now estimated that more than 6% of sun-like stars have a detectable ‘wobble’ due to the orbit of at least one Jupiter-mass planet. At the time of writing (28 February 2007), the total number of planets listed in the Extrasolar Planets Encyclopedia (http://www.obspm.fr/planets) was 215 in 185 planetary systems (including 21 multiple planet systems). Most of the recent radial velocity planet searches have been able to detect velocity variations as small as 10 m/s (Marcy et al., 2003) and so a Sun-Jupiter system (for which the Sun’s radial velocity is 13.2 m/s) should have been just about detectable and, indeed, such planets are now regularly being found. For example (Wittenmyer et al., 2007) report the discovery of 47 UMa c, a planet with mass 1.34 M_J, low eccentricity and an orbital radius $a = 7.73$ AU. Recent improvements have meant that current observations can now achieve even greater accuracies of 3 m/s and thus the number of planets detectable by this technique is steadily increasing. In addition, the current data sets only last for $\sim$ 10 years. As measurements continue, and the sensitivity improves, the discovery of more Jupiter-like planets orbiting far from their star with longer periods is expected. At the time of writing 26 exoplanets have now been catalogued with an orbital distance greater than 3 AU.

1.2.2 Astrometry

Given a sequence of observations of a star's position of sufficiently high accuracy relative to the celestial sphere, the reflex motion of the star caused by the orbit of a planet around it can be detected. This can be used to determine both the absolute mass and orbital inclination of a planet. Considering the motion of the star and planet about their common centre of mass we can see that the reflex amplitude of the star is $a_* = a_p M_p / M_*$, where a_* and a_p are the distances from the centre-of-mass to the star and planet respectively. Thus, this method is most effective for large mass planets orbiting at some distance from their parent stars. In addition, since what is actually measured is the angular position of the star, the method is clearly best for planetary systems within a few parsecs of the Earth.

The accurate measurement of a star's position over a number of years is a challenging task. Current optical systems have an absolute accuracy of a few milliarcseconds. However this precision can be improved through the use of long-baseline interferometry. The VLT and Keck currently have programmes to do this and are expected to achieve accuracies of 30 μas (microarcseconds), which should be sufficient to observe the reflex motion of the stars of several extrasolar giant planets already discovered. In addition, there are two space missions planned to exploit this technique. The NASA SIM (Space Interferometry Mission) is due for launch sometime betwee 2009 and 2015 and will be able to achieve 1 μas accuracy, while the ESA GAIA spacecraft, which is a follow-up to ESA's Hipparcos mission, is due to launch in 2011. Although not an interferometric instrument, GAIA aims to observe 1 billion stars with magnitude brighter than 20, with an accuracy of 10–20 μas at magnitude 15.

1.2.3 Transit Detections

For extrasolar planets, there is a small, but finite, chance that the orbital inclination i will be very close to 90° and thus that a planet will periodically pass between the planet's star and the Earth. If the planet is sufficiently large, then the drop of intensity of the starlight can be detected and used to determine both i and also the radius of the planet.

The first published detection of a planetary transit (using the STARE transit camera (Charbonneau et al., 2000)), was of the planet HD 209458 b, which orbits its star at a distance of 0.046 AU in a period of 3.5 days (Henry et al., 2000). The transit was observed the next year with the Hubble Space Telescope (HST) (Fig. 1.2) and Brown et al. (2001) concluded, from the transit depth, that the planet had a radius of 1.35 R_J (where R_J is the radius of Jupiter). This figure has recently been revised to 1.32 R_J (Knutson et al., 2007).

Assuming HD 209458 b to be typical, and until more transits of this type are observed there is no reason to think otherwise, these observations showed that the massive, close-orbiting planets discovered by the radial velocity survey were not just rocky cores, but large Jupiter-sized objects. The radius observed is considerably larger than that expected from a planet cooling in isolation and Burrows et al.

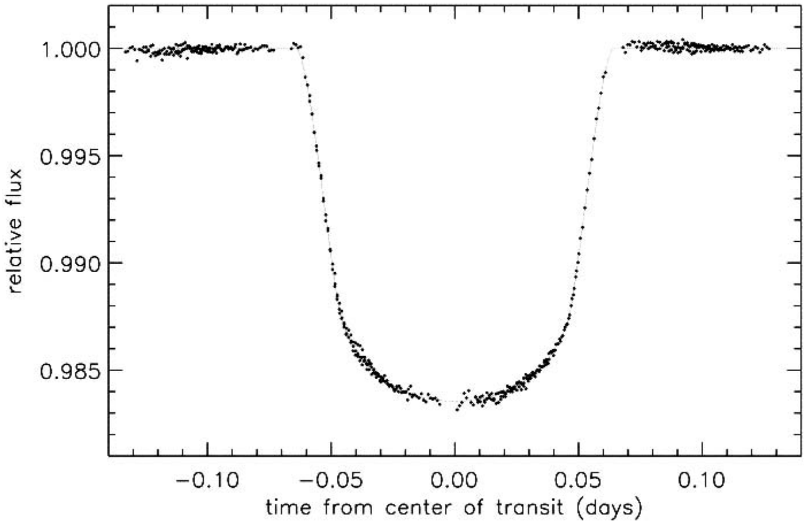

Fig. 1.2. HST observation of transit of HD 209458 b (Brown et al., 2001)

(2000) proposed that irradiation from the star inhibits convection and thus cooling/contraction. This idea was developed by Bodenheimer et al. (2001) and Guillot and Showman (2002).

A number of other extrasolar planetary transits have been observed since 1999, using projects such as OGLE (Sect. 1.2.4). Most lead to a dip in intensity of the order of 1%, and at these levels care must be taken to ensure that phenomena such as sunspot variations or isolated or blended eclipsing binary systems are not mistaken for planet detections (e.g. Mandushev et al., 2005; O'Donovan et al., 2006b, 2007).

Transit Spectroscopy

Soon after the first transit of HD 209458 b was observed, it was realised that observations at a number of different wavelengths might be used to infer the atmospheric transmission of the planet's atmosphere, since a planet's effective cross-sectional area will be larger at wavelengths where its atmosphere is more strongly absorbing than at others. Just such a study is reported by Charbonneau et al. (2002) who used HST observations near 600 nm to search for the atmospheric sodium absorption lines predicted for 'hot Jupiters' by radiative transfer models such as Sudarsky et al. (2003). The absorption line was duly detected, the first ever detection of an exoplanetary atmosphere, although the magnitude of the absorption was found to be less than that predicted by cloud-free radiative transfer models suggesting that clouds high in the atmosphere of this planet reduce the absorption band depth. Brown et al. (2002), Richardson et al. (2003a) and Richardson et al. (2003b) extended this campaign to the infrared, searching for CO, H_2O and CH_4 absorption, and recently Deming et al. (2005) detected a weak absorption due to CO at 4325 cm^{-1} and also suggested the presence of a high level cloud at, or above, 3.3 mbar.

In addition to direct detection of atmospheric absorption during transits, a gas giant orbiting as close to its star as HD 209458 b will get very hot in its upper atmosphere leading possibly to exospheric loss. Vidal-Madjar et al. (2003) report HST observations of atomic hydrogen absorption of starlight during several transits of HD 209458 b. They interpret this observation as being due to absorption by hydrogen atoms that have exospherically escaped the planet's atmosphere and are now beyond the Hill radius[2] of the planet. They further conclude that if the timescale for this evaporation is comparable to the lifetime of the stellar system then it may explain why so few 'hot Jupiters' are found orbiting with periods less than ~ 3 days. More recent HST observations by Vidal-Madjar et al. (2004) have also detected exospherically escaping carbon and oxygen atoms. Such atoms should be too heavy to escape by the Jean's mechanism, responsible for the hydrogen escape, and instead Vidal-Madjar et al. (2004) suggest that hydrodynamic escape (or 'blow-off') is responsible, whereby the outward flow of exospherically escaping hydrogen atoms carry with them heavier atoms such as carbon and oxygen.

1.2.4 Microlensing

For several years now there have been campaigns to observe galactic bulge microlensing events, with a view to searching for dark matter and extrasolar planets. In this technique, light from a distant (source) star is observed as another star at intermediate distance (the lens star) passes close to, or in front of it. Light from the source star is gravitationally bent around the lens star and thus its apparent magnitude changes during the event. Two such campaigns are OGLE (Udalski, 2003) and MOA (Bond et al., 2001). In addition to lensing events, such programmes are also sensitive to planetary transits and to date, OGLE has detected the transits of five previously unknown extrasolar planets.

In 2003, both observatories observed a remarkable microlensing event shown in Fig. 1.3 where, in addition to the central peak in source star brightness due to the gravitational lensing of the lens star, two additional sharp peaks were observed which are interpreted as being due to the microlensing of a planetary companion to the lens star. Bond et al. (2004) conclude, assuming the lens star to be a main sequence M dwarf, that the planet has a mass of 1.5 M_J, and orbits the lens star at a distance of approximately 3 AU.

OGLE has now detected three further planets through gravitational microlensing events. For future observations we will see later in Sect. 1.4 that gravitational lensing is the only detection method that is capable of sensing terrestrial planets orbiting some distance from their stars (dubbed 'cool Earths'). In addition to the continuation of the OGLE and MOA campaigns, other ground-based campaigns include PLANET, which is a collaboration of telescopes in the southern hemisphere observing since 1995. The sensitivity of microlensing campaigns to 'cool Earths' would be further advanced by placing the telescope in space and proposed mis-

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[2] The Hill radius gives the limit of the gravitational sphere of influence of a body in orbit about another heavier body, in this case the central star.

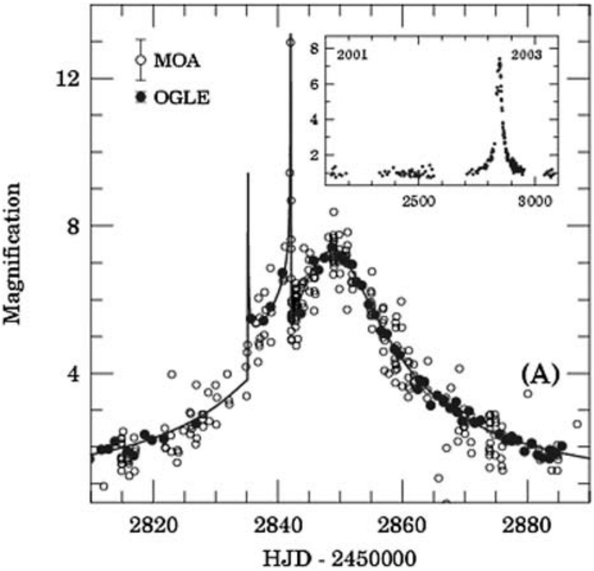

Fig. 1.3. Observation of gravitational microlensing by a planet by OGLE (Bond et al., 2004). Inset panel shows all OGLE data from 2001 to 2003, while the main figure shows a close-up of the data for 2003 for both OGLE and MOA.

sions include GEST (Galactic Exoplanet Survey Telescope) and Microlensing Planet Finder (MPF).

1.3 Properties of Observed Extrasolar Planets

So many planets have now been found that it is possible to consider the statistics of the mass and orbital parameter distributions, as has been done by Collier Cameron (2002), and Marcy et al. (2003). Radial velocity measurements can only provide information on the distribution of $M_p \sin i$. However, it can be shown (Jorissen et al., 2001) that for a random distribution of planetary systems, the distribution of $M_p \sin i$ is very close to the distribution of M_p and thus statistical conclusions on the overall mass distribution can be inferred from the distribution of $M_p \sin i$ for known exoplanets, shown in Fig. 1.4.

Considering the selection effects of radial velocity measurements, a predominance of heavy planets might be expected. However, most of the planets discovered so far have $M_p \sin i < 10M_J$, and the distribution of planets rises rapidly for smaller masses. A power law fit to the distribution is also plotted in Fig. 1.4, where the number of planets N has been assumed to vary with planetary mass as $N = \alpha(M_p \sin i)^{\beta}$. Fitting only to the well sampled distribution where $M_p \sin i < 4M_J$, values of $\alpha = 44.98$ and $\beta = -0.95$ are derived, which are found to reasonably well ap-

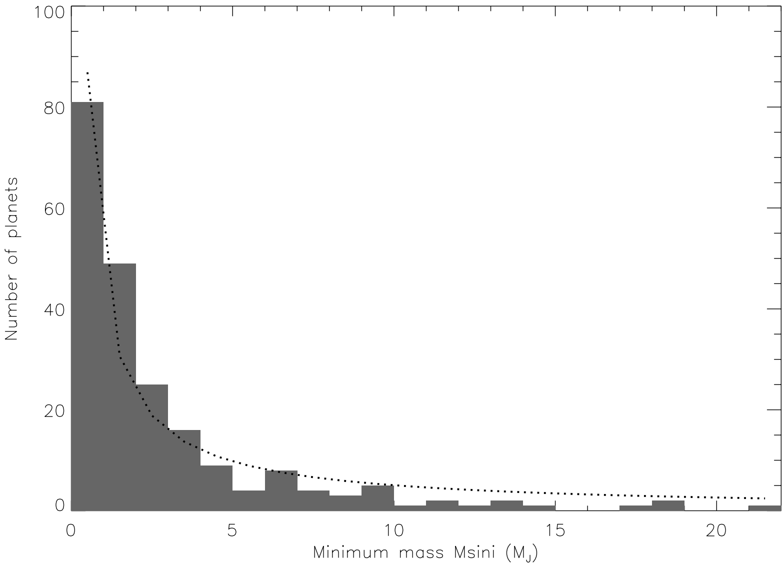

Fig. 1.4. Distribution of $M_p \sin i$ of currently known exoplanets. Also plotted is the curve $N = \alpha(M_p \sin i)^\beta$, where $\alpha = 44.98$ and $\beta = -0.95$, which is described in the text

proxinate the rest of the distribution. Hence, to first order it would appear that the number of planets falls approximately linearly with the planetary mass.

The smallest exoplanets discovered to date are OGLE-05-390L b and GJ 876 d (Rivera et al., 2005) which have estimated masses of only $\sim 5.5 M_{Earth}$ and $\sim 7.5 M_{Earth}$, respectively. In contrast, there is an apparent absence of heavy extrasolar planets with mass above the deuterium-burning limit for brown dwarfs of $\sim 13.6 M_J$ (Lewis, 2004). This apparent absence of very large mass planets has become known as the 'Brown Dwarf Desert' and it has been suggested that brown dwarfs might be formed by a different process from planets, leading to them orbiting at much greater distances than is currently detectable with the radial velocity technique. However, very recently a few heavy mass exoplanets have been discovered, the heaviest being GQ Lup b and HD 41004 B b which have an estimated $M_p \sin i$ of $21.5 M_J$ and $18.4 M_J$ (Zucker et al., 2004) respectively. Hence, the 'Brown Dwarf Desert' may prove not to be quite so barren as has been previously thought, supporting the suggestion of Jorissen et al. (2001) that there is no reason to ascribe the transition between giant planets and brown dwarfs to the threshold mass of deuterium ignition.

The distribution of exoplanet orbital periods is shown in Fig. 1.5, which appears to have a slight bimodal distribution, with peaks at 3 days and 500 days.

The distribution of exoplanet orbit radii is shown in Fig. 1.6 and it is found that a large fraction of known exoplanets orbit within 1 AU. However, given that planets with larger orbital distances take longer to orbit and current observation programmes have only been running for 10 years or so and are becoming more

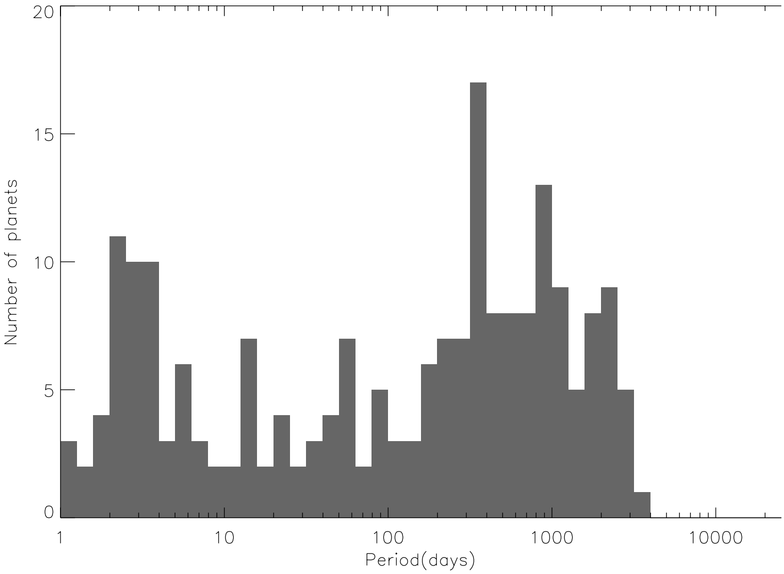

Fig. 1.5. Orbital period distribution of known exoplanets.

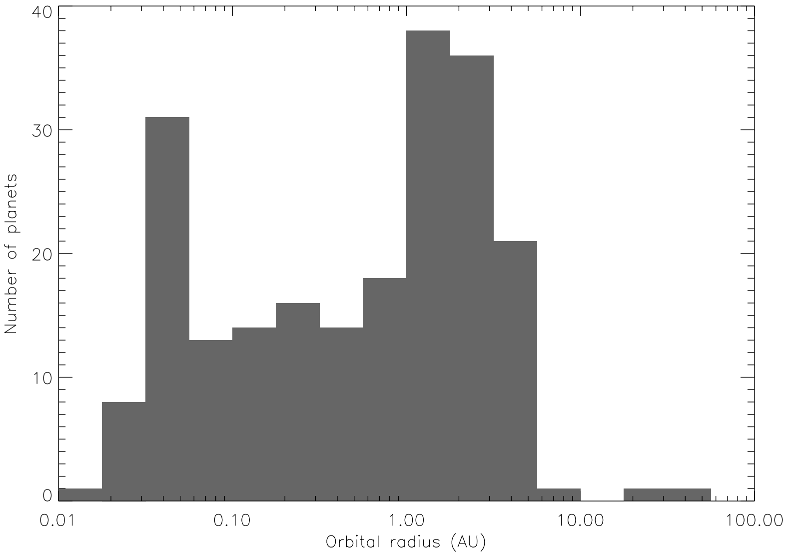

Fig. 1.6. Orbital radius distribution of known exoplanets.

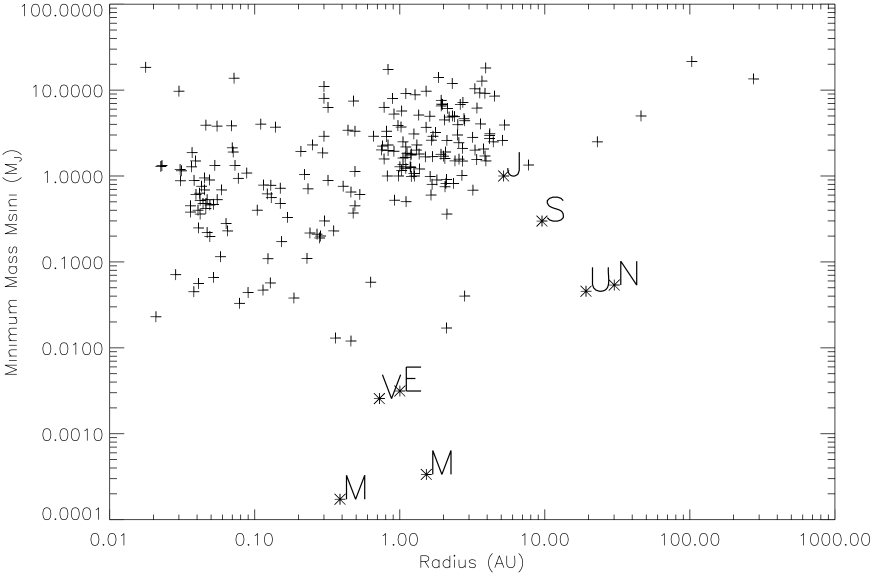

Fig. 1.7. Distribution of mass and radius for known exoplanets. Solar System planets are indicated by letter.

precise all the time, there is good reason to suspect that there is a large population of planets orbiting beyond 3 AU (Marcy et al., 2003) which will soon be detected.

Fig. 1.7 shows $M_p \sin i$ for known exoplanets plotted against their orbital distance and there can be seen to be a general decrease in the number of massive planets ($M_p > 4M_J$) orbiting within 0.3 AU. Such planets would be eminently detectable using the radial velocity method so we can be confident that they are really not there. A possible explanation for this is that the migration mechanism of massive planets is either inefficient within 0.3 AU or too efficient and thus that massive planets straying within 1 AU fall all the way into the star (Marcy et al., 2003). Alternatively, as discussed in Sect. 1.2.3 it may be that planets closer than this quickly evaporate (Vidal-Madjar et al., 2003).

There is a massive and uniform spread in the eccentricities of exoplanets between 0 and 0.9 (Fig. 1.8), which suggests that there is a common mechanism for pumping the eccentricity of extrasolar planets. It can also be seen from Fig. 1.8 that the eccentricity distribution for planets in multiple-planet systems is indistinguishable from that for single planet systems. For the multiple planet systems known, eccentricity pumping may result from planets migrating in their circumstellar disc, leading to occasional mutual capture and resonance. Subsequent close encounters may lead to scattering and ejection of planets. This scenario explains the orbital resonances commonly seen in multiple-planet systems and also the occurrence of 'hierarchical' systems (ones with only a few, widely separated planets), where some of the planets have presumably been ejected. Single planet systems may be the end result of such interactions, where all other giant planets have been lost through ejec-

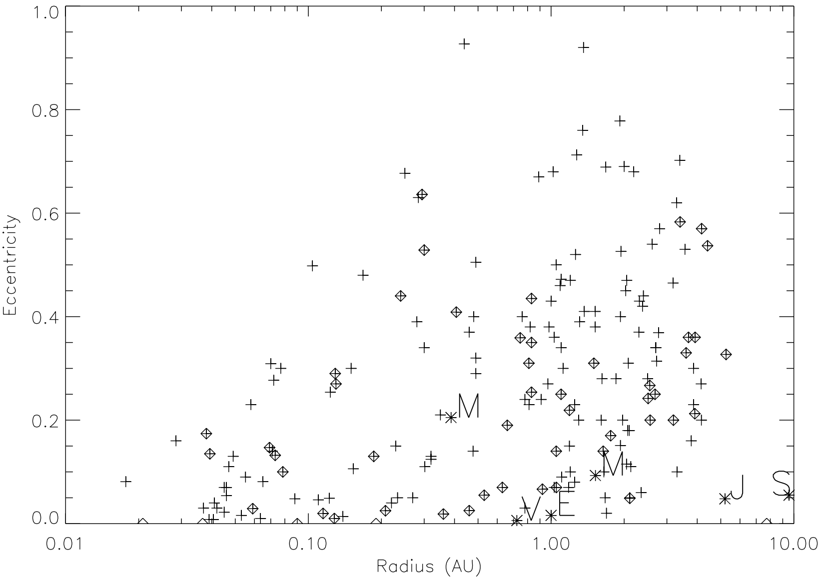

Fig. 1.8. Distribution of eccentricity and radius for known exoplanets. In this plot Solar System planets are indicated by letter and planets in multi-planet systems are indicated by diamonds.

tion. Alternatively it could just be that single planet systems actually have other planets which have just not been detected yet.

An intriguing discovery is of a multiple planet system around the star HD 69830 which comprises three Neptune mass planets (Lovis et al., 2006) and possibly also an asteroid belt (Beichman et al., 2005).

It has been pointed out by Charbonneau (2006) that the precision achieved by Lovis et al. (2006) means that it is now more likely that terrestrial-type planets may be detected by the radial-velocity method, since the Sun is unusually hot and massive compared to other nearby stars. The 'habitable zone' of other stars is likely to be closer to the star and coupled with their lower mass the 'wobble' introduced by a terrestrial planet's mass may now be just about detectable.

The analysis of the metallicity of stars which have planetary companions is very revealing (Fig. 1.9). The [Fe/H] ratio is defined as the abundance of iron in a star to that found in the Sun, expressed on a logarithmic scale. Thus a star with [Fe/H]=1 has 10 times the abundance of iron (and other metals) as the Sun. From Fig. 1.9 it can be seen that, as found by Fischer and Valenti (2003) and Santos et al. (2004), the distribution rises rapidly at the high metallicity end and thus the great majority of known exoplanets orbit stars with a metallicity equal to, or greater than that of our Sun (Sudarsky et al., 2003). These observations strongly suggest that the presence of dust in proto-stellar nebulas is very important for the formation of planets and thus favours the core-accretion model of planetary formation (Pollack et al., 1996).

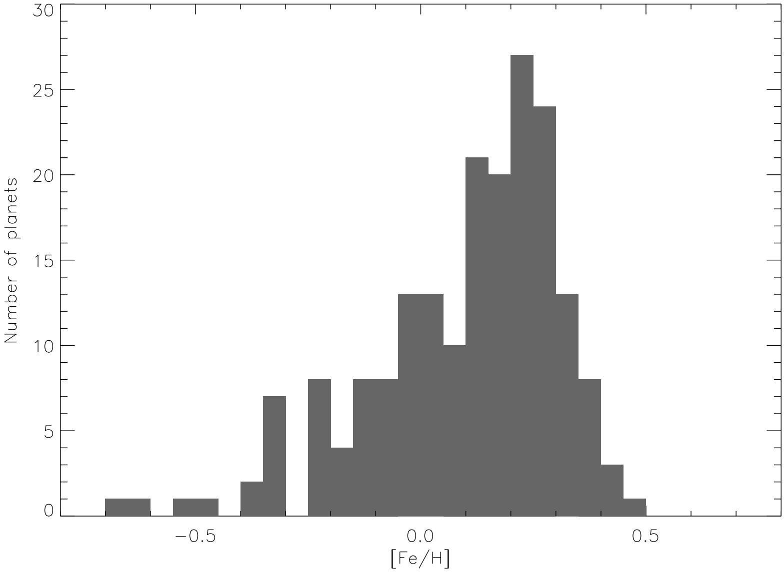

Fig. 1.9. Distribution of star metallicity for known exoplanetary systems.

1.4 Sensitivity and Future Methods for Detection of Extrasolar Planets

We have seen that there are a number of ways of detecting the existence of extrasolar planets, most indirect. All the techniques have their own advantages and disadvantages and the different selection effects of these detection methods are summarised in Fig. 1.10, on which are plotted the mass and orbital radii of known exoplanets, together with characteristics of the Solar System planets.

Currently employed detection methods are biased towards close-orbiting heavy planets and thus very few lighter terrestrial-like planets have so far been found, with the lowest mass for planet orbiting an active star so far being estimated as $5.5M_{Earth}$ (Sect. 1.3). Three earth-mass extrasolar planets have actually been discovered, but these do not orbit a main sequence star, but instead have been observed orbiting the pulsar PSR 1257+12 (Wolszczan and Frail, 1992; Wolszczan, 1994). Although no terrestrial planets have so far been discovered, there is no reason to think that they are not present and as measurement techniques improve, it is widely hoped that terrestrial planets may soon start being detected.

As can be seen, the radial velocity technique is best for detecting heavy, close orbiting planets, and thus the planets found so far are clustered in the top left corner of Fig. 1.10. The limit of detectability of existing measurements is shown, together with the expected improvement due to ever increasing sensitivity and longer observation runs. Radial velocity programmes currently under way include the Anglo-Australian Planet Search (e.g. Carter et al., 2003), the California and Carnegie Planet Search,