Part I

Planetary systems and the origins of life

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Ralph Pudritz, Paul Higgs, and Jonathon Stone
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Observations of extrasolar planetary systems

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1.1 Introduction

A decade has passed since the first discovery of an extrasolar planet by Mayor and Queloz (1995) and its confirmation by Marcy *et al.* (1997). Since this groundbreaking discovery, about 190 planets have been found around nearby stars, as of May 2006 (Schneider, 2006). Here we shall review the main methods astronomers use to detect extrasolar planets, and the data we can derive from those observations.

Aitken (1938) examined the observational problem of detecting extrasolar planets. He showed that their detection, either directly or indirectly, lay beyond the technical horizon of his era. The basic difficulty in directly detecting planets is the brightness ratio between a typical planet, which shines mainly by reflecting the light of its host star, and the star itself. In the case of Jupiter and the Sun, this ratio is 2.5×10^{-9}. If we keep using Jupiter as a typical example, we expect a planet to orbit at a distance of the order of 5 astronomical units (AU, where 1 AU = 1.5×10^{11} m = distance from Earth to Sun) from its host star. At a relatively small distance of 5 parsecs from the Solar System, this translates into a mean angular separation of the sources on the sky of 1 arcsecond. Therefore, with present technology, it is extremely demanding to directly image any extrasolar planet inside the overpowering glare of its host star, particularly from the ground, where the Earth's atmosphere seriously affects the observations. Nevertheless, significant advances have been made in the fields of coronagraphy and adaptive optics and positive results are very likely in the coming few years.

The vast majority of the known extrasolar planets were detected by *indirect* means, which matured in 1995 to allow the detection of the giant planet around the star 51 Peg through the spectroscopic *radial-velocity* (RV) technique. RV monitoring is responsible for most of the known extrasolar planets. *Transit* detection, another indirect method, has gained importance in the last few years,

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already yielding a few detections. The next two sections will review those two methods, their advantages and their drawbacks. Section 1.4 will provide a brief account of the emerging properties of the extrasolar planet population. In Section 1.5 we will briefly review other possible methods of detection. Section 1.6 will conclude the chapter with some predictions about future observations from space.

1.2 RV detections

Consider a star–planet system, where the planet's orbit is circular, for simplicity. By a simple application of Newton's laws, we can see that the star performs a reflex circular motion about the common centre of mass of the star and planet, with the same period (P) as the planet. The radius of the star's orbit is then given by:

$$a_\star = a\left(\frac{M_\mathrm{p}}{M_\star}\right), \tag{1.1}$$

where a is the radius of the planet orbit, and M_p and $M_\star$ are the planet mass and the star mass, respectively. The motion of the star results in the periodic perturbation of various observables that can be used to detect this motion. The RV technique focuses on the periodic perturbation of the line-of-sight component of the star's velocity.

Astronomers routinely measure RVs of objects ranging from Solar System minor planets to distant quasars. The basic tool to measure RV is the spectrograph, which disperses the light into its constituent wavelengths, yielding the stellar *spectrum*. Stars like our Sun, the so-called *main-sequence* stars, have well-known spectra. Small shifts in the wavelengths of the observed spectrum can tell us about the star's RV through the *Doppler effect*. Thus, a Doppler shift of $\Delta\lambda$ in a feature of rest wavelength λ in the stellar spectrum corresponds to an RV of:

$$v_\mathrm{r} = \frac{\Delta\lambda}{\lambda}c, \tag{1.2}$$

where c is the speed of light.

The most obvious parameters which characterize the periodic modulation of the RV are the period, P, and the semi-amplitude, K (Figure 1.1(a)). These two parameters are related to the planet mass via the general formula (e.g., Cumming *et al.* (1999)):

$$K = \left(\frac{2\pi G}{P}\right)^{\frac{1}{3}} \frac{M_\mathrm{p}\sin i}{(M_\star + M_\mathrm{p})^{\frac{2}{3}}} \frac{1}{\sqrt{1-e^2}}. \tag{1.3}$$

In this formula G is the universal gravitational constant, and e is the orbital eccentricity. The inclination of the orbital axis relative to the line of sight is denoted

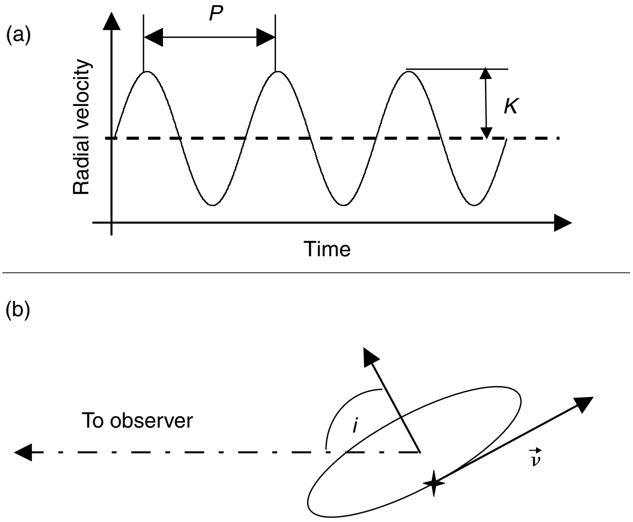

Fig. 1.1. (a) A schematic illustration of a periodic RV curve of a planetary orbit, showing the two quantities P (period) and K (semi-amplitude). (b) Visualization of the inclination angle (i), the angle between the orbital axis and the line of sight.

by i (Figure 1.1(b)). In a circular orbit we can neglect e and, assuming that the planet mass is much smaller than the stellar mass, we can derive the empirical formula:

$$K = \left(\frac{P}{1\ \mathrm{day}}\right)^{-\frac{1}{3}} \left(\frac{M_\star}{M_\odot}\right)^{-\frac{2}{3}} \left(\frac{M_\mathrm{p} \sin i}{M_\mathrm{J}}\right) 203\ \mathrm{m\ s^{-1}}. \tag{1.4}$$

M_J denotes Jovian mass, and $M_\odot$ stands for the Solar mass. (Extrasolar planets are typically the mass of Jupiter, hence we normalize our formulae using 'Jovian mass'.)

Close examination of Equation (1.4) reveals several important points. First, K has a weak inverse dependence on P, which means that the RV technique is biased towards detecting short-period planets. Second, the planet mass and the inclination appear only in the product $M_\mathrm{p} \sin i$, and therefore they cannot be derived separately using RV data alone. In principle, a planetary orbit observed edge-on (i close to 90°) will have exactly the same RV signature as a stellar orbit observed face-on (i close to 0). Statistics help to partly solve the conundrum, since values of $\sin i$ which are close to unity are much more probable than smaller values (e.g., Marcy and Butler (1998)). In fact, for a randomly oriented set of orbits, the mean value of $\sin i$ is easily shown to be $4/\pi \approx 0.785$. Obviously, a better solution would be to seek independent information about the inclination.

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Equation (1.4) shows the order of magnitude of the desired effect – tens or hundreds of metres per second. Detecting effects of this magnitude requires a precision of the order of metres per second. Such a precision was almost impossible to achieve before the 1990s. Before that time, the only claim of a very low-mass companion detected via RV was of the companion of the star HD 114762. The semi-amplitude of the RV variation was about 600 m s^{-1}, and the companion mass was found to be around 10 M_J (Latham *et al.*, 1989; Mazeh *et al.*, 1996). Although the existence of this object is well established, the question of its planetary nature is still debated. Alternatively, it could be a *brown dwarf* – an intermediary object between a planet and a star. The detection of smaller planet candidates had to await the development of instruments that could measure *precise* RVs.

Campbell and Walker (1979) were the first to obtain RVs of the required precision. They introduced an absorption cell containing hydrogen fluoride gas in the optical path of the stellar light in order to overcome systematic errors in the RVs, using the known spectrum of the gas for calibration. They carried out a pioneering survey of 16 stars over a period of 6 years, which yielded no detections, probably because of the small sample size (Campbell *et al.*, 1988).

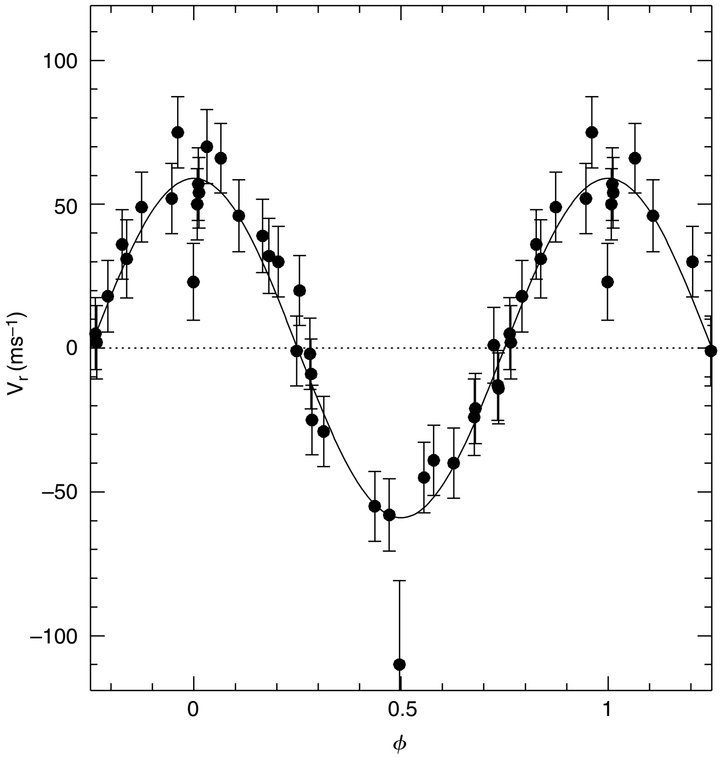

Fig. 1.2. The phase-folded RV curve of 51 Peg, from Mayor and Queloz (1995).

The first planet candidate detected using precise RV measurements was 51 Peg b. Mayor and Queloz (1995) used the fibre-fed ELODIE spectrograph in the Haute-Provence Observatory (Baranne *et al.*, 1996), and obtained an RV curve of 51 Peg corresponding to a planet with a mass of $0.44\,M_{\mathrm{J}}$ and an orbital period of 4.23 days (Figure 1.2). This short period means an orbital distance of 0.05 AU from the host star. The discovery was soon confirmed by Marcy *et al.* (1997), using the Hamilton echelle spectrograph at the Lick Observatory, with the iodine absorption cell technique (Butler *et al.*, 1996). This proximity to the host star was a major surprise and it actually contradicted the previous theories about planetary system formation. This discovery, and those of many similar planets that followed (now nicknamed 'Hot Jupiters'), led to a revision of those theories, and to the development of the planetary migration paradigm (e.g., Lin *et al.* (1996)). The current state of the formation and evolution theories is reviewed in Chapter 3.

Since that first detection, several groups have routinely performed RV measurements. The most prominent groups are the Geneva group, using fibre-fed spectrographs (Baranne *et al.*, 1996), and the Berkeley group, using the iodine-cell technique (Butler *et al.*, 1996).

1.3 Transit detections

We have seen in Section 1.2 that the basic drawback of the RV method is the lack of independent information about the orbital inclination, which leads to a fundamental uncertainty in the planet mass. Currently, the most successful means of obtaining this information is via the detection of planetary *transits*. In the Solar System, transits are a well-known rare phenomenon in which one of the inner planets (Mercury or Venus) passes in front of the solar disk. The most recent Venus transit occurred on 8 June 2004, and attracted considerable public attention and media coverage. Extrasolar transits occur when an extrasolar planet passes in front of its host-star disk. Obviously, we cannot observe extrasolar planetary transits in the same detail as transits in the Solar System. With current technology, the only observable effect would be a periodic dimming of the star light, because the planet obscures part of the star's surface. Thus, transits can be detected by *photometry*, i.e., monitoring the stellar light intensity.

The probability that a planetary orbit would be situated in such a geometric configuration to allow transits is not very high. For a circular orbit, simple geometrical considerations show that this probability is:

$$\mathcal{P} = \frac{R_\star + R_{\mathrm{p}}}{a}, \tag{1.5}$$

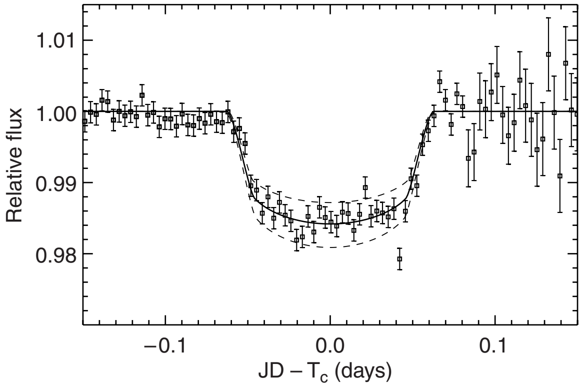

Fig. 1.3. The transit light curve of HD209458, from Charbonneau *et al.* (2000).

where $R_\star$ and R_p are the radii of the star and the planet, respectively (e.g., Sackett (1999)). For a typical hot Jupiter, this probability is about 10%.

The idea of using transits to detect extrasolar planets was first raised by Struve (1952), but the first extrasolar transit was observed only in 1999. Mazeh *et al.* (2000) detected a planet orbiting the star HD 209458, using 'traditional' RV methods. Soon after the RV detection, Charbonneau *et al.* (2000) and Henry *et al.* (2000) detected a periodical dimming of the light coming from HD 209458, at exactly the predicted orbital phase and with the same period as the RV variation, of 3.52 days. The light dimmed by about 1.5% for about 1.5 hours (Figure 1.3). The two teams detected the transits using small and relatively cheap telescopes, demonstrating that it was realistic to achieve the required photometric precision with ground-based observations.

The depth of the transit (i.e., the amount by which the light intensity drops) depends on the fraction of the stellar disk obscured by the planet. Thus, assuming there is a reasonable estimate of the star's radius, we can use the depth to derive the planet radius. This is the first direct estimate we have of a physical property of the planet itself. Obviously, the detection of transits immediately constrains the orbital inclination (i) to values close to 90° (transits occur only when we observe the orbit edge-on or almost edge-on). Furthermore, the transit duration depends strongly on the orbital inclination, and we can use it to explicitly derive i (e.g., Sackett (1999)). Thus, in combination with RV data, we can finally obtain a measurement of the planet mass, M_p.

Brown *et al.* (2001) used the Hubble Space Telescope (HST) to obtain a very precise light curve of HD 209458. This light curve led to a very precise estimate of the planet radius: 1.347 Jupiter radii (R_J). Using the inclination and the mass estimate from the RV orbit, the planet mean density could be derived: 0.35 g cm^{-3}.

The special circumstances of a transiting extrasolar planet were exploited by many more observations of HD 209458, with new clues about its atmosphere. Those observations are reviewed in Chapter 2.

The successful observations of HD 209458 encouraged many teams to try to detect more transiting extrasolar planets. Currently about 25 surveys are being conducted by teams around the world (Horne, 2006). Some of these surveys use small dedicated telescopes to monitor nearby stars (which are relatively bright) in large fields of view, like TrES (Alonso *et al.*, 2004) or HATnet (Bakos *et al.*, 2004). Other surveys, such as OGLE-III (Udalski *et al.*, 2002) or STEPSS (Burke *et al.*, 2004), focus on crowded fields like the Galactic Centre or globular clusters, and monitor tens of thousands of stars.

So far, the only successful surveys have been OGLE, with five confirmed planets, and TrES and XO, with one planet each. Their success highlights the difficulties such surveys face, and the problems in interpreting the observational data. The basic technical challenge is transit detection itself. The transits last only a small fraction of the planet's orbital time around its central star, and the drop in the stellar brightness is usually of the order of 1–2% at most. The first obvious challenge is to reach a sufficient photometric precision. The next challenge is to obtain sufficient phase coverage, on the observational front, and efficient signal analysis algorithms, on the computational front.

The OGLE project has yielded so far 177 transiting planet candidates (Udalski *et al.*, 2004). However, only five thus far have been confirmed as planets. This is due to the fundamental problem in using photometry to detect giant planets. Since the transit light curve alone does not provide any information regarding the mass of the eclipsing companion, we have to rely on its inferred radius to deduce its nature. However, it is known (e.g., Chabrier and Baraffe (2000)) that in the substellar mass regime, down to Jupiter mass, the radius depends extremely weakly on the mass. Therefore, even if we detect what seems to be a genuine transit light curve, the eclipsing object may still be a very low-mass star or a brown dwarf. The only way to determine its nature conclusively is through RV follow-up that would derive its mass. Thus, while only five of the OGLE candidates have been shown to be planetary companions, many others have been identified as stellar companions.

The proven non-planetary OGLE candidates demonstrate the diversity of events that can be mistaken for planetary transits. OGLE-TR-122 is a perfect example of a low-mass star which eclipses its larger companion, like a planet would. Only RV follow-up determined its stellar nature (Pont *et al.*, 2005). Other confusing configurations are 'grazing' eclipsing binary stars, where one star obscures only a tiny part of its companion, and 'blends', where the light of an eclipsing binary star is added to the light of a background star, effectively reducing the measured eclipse depth. In principle, these cases can be identified by close scrutiny of the light curve

(Drake, 2003; Seager and Mallén-Ornellas, 2003), or by using colour information in addition to the light-curve shape (Tingley, 2004). However, the most decisive identification is still through RVs.

Although transit detection alone is not sufficient to count as planet detection, transit surveys still offer two important advantages over RV surveys. First, they allow the simultaneous study of many more stars – the crowded fields monitored by transit surveys contain thousands of stars. Second, they broaden the range of stellar types which we examine for the existence of planets. While obtaining the required precision of RV measurements puts somewhat stringent constraints on the stellar spectrum, transit detection relies much less on the stellar type. The star simply has to be bright enough and maintain a stable enough brightness so that we can spot the minute periodical dimming caused by the transiting planet. Since stellar radii depend only weakly on the stellar mass, we should be able to detect planetary transits even around stars much hotter (and therefore more massive) than the Sun.

1.4 Properties of the extrasolar planets

As of May 2006, 193 extrasolar planets are known (Schneider, 2006). This number, although not overwhelming, is already enough to make some preliminary statistical observations. Obviously, these findings have a significant effect on the development of theories concerning the formation and evolution of planets in general, and the Solar System in particular. We shall now review the most prominent features of the growing population of extrasolar planets.

1.4.1 Mass distribution

The definition of planets, especially a definition that would distinguish them from stars, has been a central research theme since the very first detections. The most obvious criterion, which remains the most commonly used one, is simply the object mass. The boundary between stars and substellar objects, at $0.08\,M_\odot$, is already well known and physically understood (the mass above which hydrogen burning is ignited). A similar boundary that would apply for planets was sought. This was set at the so-called ‘deuterium burning limit’, at $13\,M_\mathrm{J}$ (Burrows *et al.*, 1997). This arbitrary limit is not related to the hypothesized formation mechanisms. The tail of the mass distribution of very low-mass companions suggests that objects with masses as large as $20\,M_\mathrm{J}$ exist. The question of whether the mass distribution of the detected planets indeed exhibits two distinct populations – planets and stars – remains. The evidence is mounting that this is indeed the case. It seems that the mass regime between $20\,M_\mathrm{J}$ and $0.08\,M_\odot$ is underpopulated (Jorissen *et al.*, 2001;

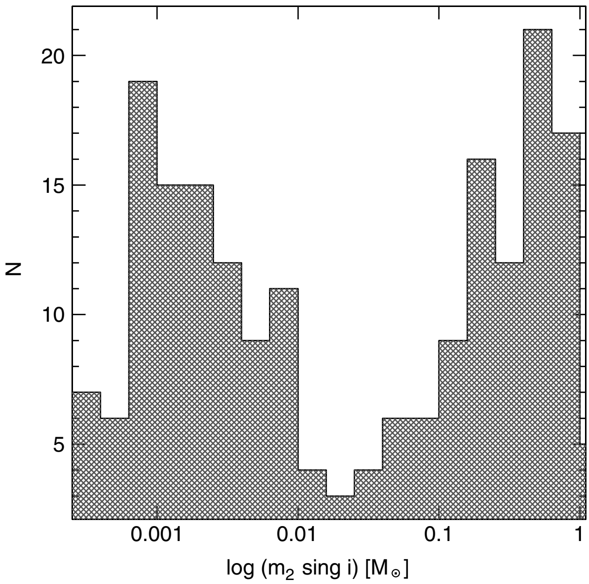

Fig. 1.4. The mass distribution of companions to solar-type stars. Note the dearth of planets at masses between 0.02 and 0.08 solar masses – 'the Brown-Dwarf Desert'. From Udry *et al.* (2004).

Zucker and Mazeh, 2001b), as can be seen in Figure 1.4. This depletion is nicknamed *the Brown-Dwarf Desert* (Marcy and Butler, 2000; Halbwachs *et al.*, 2000).

1.4.2 Mass–period distribution

The existence of 'Hot Jupiters' implied the possible presence of massive planets close to their host stars. Since the RV technique is mostly sensitive to short periods and massive planets, we expect to find a dense population in this part of the mass–period diagram. However, this is not the case, as was shown by Zucker and Mazeh (2002), Udry *et al.* (2002), and Pätzold and Rauer (2002). This may hint that the planetary migration process is less effective for very massive planets (Nelson *et al.*, 2000; Trilling *et al.*, 2002). Alternatively, it could mean that at very short distances the planet 'spills over' part of its mass onto the host star (Trilling *et al.*, 1998).

1.4.3 Orbital eccentricities

The second extrasolar planet detected, 70 Vir b, turned out to have a considerably eccentric orbit, with an eccentricity of 0.4 (Marcy and Butler, 1996). HD 80606 b currently holds the eccentricity record, with an eccentricity of 0.93 (Naef *et al.*, 2001). Such high orbital eccentricities were also a surprise. The matter in