Extra-solar planets: detection methods and results

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Abstract

Since 1995, more than 200 extra-solar planets have been discovered, demonstrating not only that planetary systems are common, but also that planets may come in a large variety of flavors. As the number of detections grows, statistical studies of the properties of exoplanets and their host stars can be conducted to unravel some of the key physical and chemical processes leading to the formation of planetary systems. In this paper we describe the major techniques used to search for extra-solar planets. In particular, we discuss in more detail the radial-velocity and the transit techniques, responsible for the discovery of the bulk of the known planets orbiting solar-type stars. We then present the main results from the planet surveys, describing the global properties of the newfound worlds.

Key words: Extra-solar planets, planet-search techniques, radial-velocities, spectroscopy, transits

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1 Introduction

In the early 1990's, Wolszczan and Frail (1992) made an exciting discovery of planets far from our own solar system in orbit around the pulsar PSR 1257+12. After years of frustrating results, evidence had finally been found for small orbiting bodies in distant stellar environments. At the same time, pulsars are different from our own Sun and any planets orbiting them would not be expected to harbor life as in our solar system. Furthermore, it is thought that pulsar planets are most probably second generation planets. Hypothetical planets existing by the time of the supernova explosion that gave origin to the pulsar would most probably have disappeared. For these reasons, researchers had for long been eager to find planets in orbit around Sun-like stars. But only in 1995 the first exoplanet was detected around the star 51 Pegasi (Mayor and

Preprint submitted to Elsevier *17 December 2007*

Queloz, 1995)[1].

Twelve years passed since the discovery of 51 Peg b. Today, planet hunters unveiled the presence of more than 200 exoplanets[2] using a variety of techniques. These discoveries showed the existence of planets with a huge variety of characteristics (see review by Udry and Santos, 2007), opening unexpected questions about the origin and evolution of planetary systems. In general, the observed planetary companions are very different from their Solar System couterparts. According to the theories accepted in 1995, none of these objects was supposed to exist.

The oddity of the discovered planets is illustrated by the fact that about 10% of them have orbital periods of less than 5 days (like 51 Peg b itself). Although the existence of such planets had been suggested before (Struve, 1952), their existence was unexpected because giant planets are thought to form only far from their stars, like Jupiter and Saturn (Pollack et al., 1996). Nevertheless, planet searches have revealed giant planets with orbital periods as short as 1.2 days (Konacki et al., 2003), or as long as ∼10 years (Marcy et al., 2002). Some of the planets are on eccentric orbits more typical of some comets in the Solar System (Naef et al., 2001), while others are in multiple planet systems (Butler et al., 1999; McArthur et al., 2004). Finally, while the most recently discovered planets have masses only one order of magnitude larger than Earth (Santos et al., 2004a; McArthur et al., 2004; Lovis et al., 2006; Udry et al., 2007), some behemoths have more than 15 times the mass of Jupiter (Udry et al., 2002).

The growing number of exoplanets is now allowing statistical analysis of their properties (e.g. Udry et al., 2003), as well as of their host stars (Gonzalez, 1998; Santos et al., 2004c). These studies are providing the first constraints on the physical and chemical processes involved in the formation of these systems. It is now known that planets can form far from their host stars, and later migrate inwards as a result of interactions with the proto-planetary disk (Lin et al., 1996). The interaction with other bodies may partially explain the variety of observed orbital eccentricities (e.g. Rasio and Ford, 1996). It is also known that giant planets seem to be more easily formed around solar-like stars having a higher metal content. Although many aspects are still unknown, this conclusion supports the core-accretion model for giant planet formation (e.g. Ida and Lin, 2004b).

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[1] The previously discovered radial-velocity companion around HD 114762 (Latham et al., 1989) has a minimum mass above 10 M_{Jup}, and is likely a brown-dwarf. Similarly, the detection of a planetary companion around γ Cep discussed in Walker et al. (1992) only recently was put in solid ground (Hatzes et al., 2003).

[2] For continuously updated tables see http://www.exoplanets.eu or http://exoplanet.eu

All these discoveries and studies were made possible due to the development of different planet search techniques. In this chapter we will describe the most important of these, including the astrometry, radial-velocity and transit techniques. Particular emphasis will be given to the latter two, responsible for most of the discoveries. Other methods, like the gravitational microlensing or pulsar timing will not be described here. For more details on these two techniques, we point the reader to Beaulieu et al. (2006) and Wolszczan and Frail (1992), and references therein. High angular resolution imaging will also not be deeply discussed, since other chapters in this book approach this issue. We will then present an overview of the results, and describe the statistical properties of the newfound worlds. We finish with a brief description about the future prospects in this field.

2 The search for extra-solar planets

The generally accepted picture of stellar formation teaches us that a planetary system is a natural byproduct of the stellar formation process. When a cloud of gas and dust contracts to give origin to a star, conservation of angular momentum leads to the formation of a flat disk of gas and dust around the central newborn "sun". As time passes, in a process still not completely understood, dust particles and ice grains in the disk are gathered to form the first planetary seeds (Safronov, 1969). In the "outer" regions of the disk, where ices can condensate, these "planetesimals" are thought to grow in a few million years (Pollack et al., 1996). When such a "planetesimal" achieves enough mass (about 10 times the mass of the Earth), its gravitational pull enables it to accrete gas in a runaway process that gives origin to a giant gaseous planet similar to the outer planets in our own Solar System. Later on, in the inner part of the disk, where temperatures are too high and volatiles cannot condensate, silicate particles are gathered to form the telluric planets like our Earth.

Images taken by the NASA/ESA Hubble Space Telescope (HST) revealed a multitude of such proto-planetary disks in the Orion stellar nursery (e.g. McCaughrean and O'dell, 1996). Together with the number of near-IR detections of disks around T Tauri stars (see e.g. Haisch et al., 2001), these findings show that disks are indeed very common around young solar-type stars. This supports the idea that extra-solar planets should be common. However, such systems have escaped detection until very recently. The idea of finding other planets was until the mid 90's no more than an old and fantastic dream.

The reason for this has to do with the difficulty to detect such systems. Planets are cold bodies, and their visible spectra results basically from reflected light of the parent star. As a result, in optical wavelengths the planet/stellar luminosity ratio is of the order of 10^{-9}. Seen from a distance of a few parsec, a planet is no more than a small "undetectable" speckle embedded in the diffraction and/or aberration of the stellar image. Only the development of adaptive optics imaging will enable the direct detection of exoplanets (see Sect. 4).

But a planet also induces dynamical perturbations into its "parent sun", giving the possibility to detect its presence by indirect means. Indeed, any star in a binary or multiple system will present a periodic motion about the center of mass of the system. This effect gives the possibility to indirectly detect a planet orbiting another star, by "simply" measuring this dynamical effect. As we shall see in the next paragraphs, for solar type stars this can be used to try to detect planets using two different techniques: astrometry and radial-velocities.

2.1 Astrometry

Astronomers have long tried to use the dynamical effect that a planet has on the stellar motion to measure the small astrometric periodic shift of a star as it moves about the center of mass of the star-planet system. The results were quite disappointing, with some false and discouraging detections. Only recently the first astrometric planetary motion was measured using the Hubble Space Telescope (Benedict et al., 2002).

The astrometric detection of an extra-solar planet can be described, in a very basic approach, by simple physics. The semi-major axis of the orbital motion of a star around the center of mass of a two-body system can be described by:

$$M_1\, a_1 = M_2\, a_2 \tag{1}$$

where M_1 and M_2 are the masses of the two bodies, and a_1 and a_2 the semi-major axis of their orbits. Defining $a = a_1 + a_2$ as the semi-major axis of the relative orbit (it denotes the separation of the two bodies), we can write:

$$a_1 = \frac{M_2}{M_1 + M_2}\, a \tag{2}$$

This equation relates the expected astrometric displacement a_1 of a star of mass M_1 due to the presence of a planet with mass M_2, separated by the distance a. The distance a is also related to the orbital period P by Kepler's 3rd law,

$$P^2 = \frac{a^3}{M_1 + M_2} \tag{3}$$

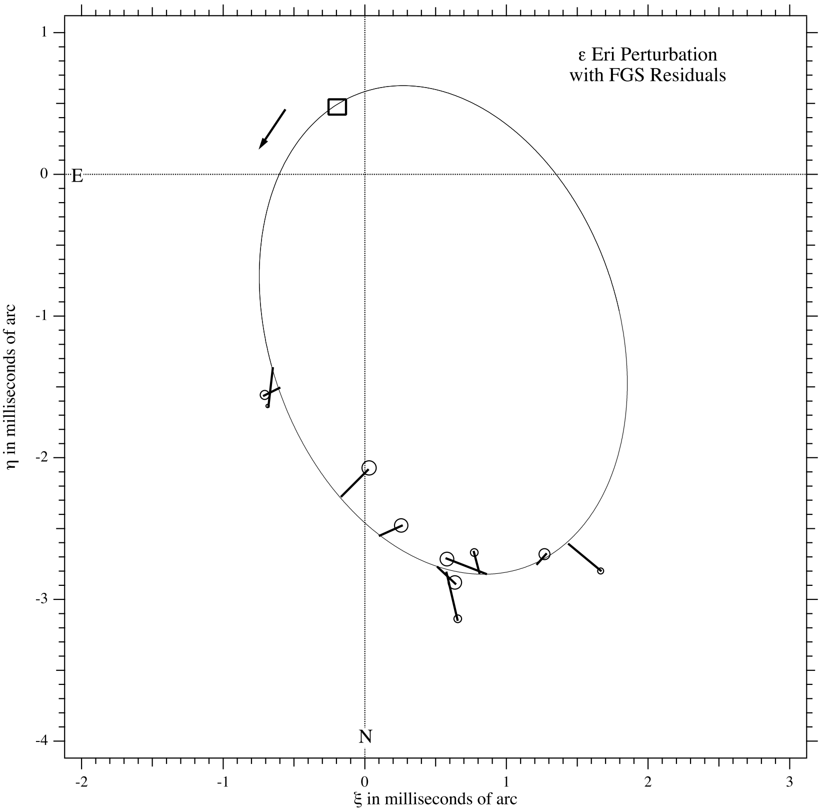

Fig. 1. Astrometric orbital solution for the star ϵ Eri, due to the orbital motion around the center of mass of its star-planet system. From Benedict et al. (2006).

In principle, if we measure a_1, a_2, and P, we can solve the system above and derive the mass of the two bodies. This is the case for some visual binary stars.

In practice, the measurement of the astrometric motion of the primary star in a star-planet system is far more complex. First, we can only hope to measure a_1 and the period P, since we are not able to directly observe the planet. To solve the above system we need, for example, to estimate the mass of the star (M_1) using stellar evolution models. Secondly, the astrometric orbit observed corresponds to the 2-dimensional projections on the celestial sphere of the true 3-dimensional orbit. Further information is required to construct the true orbit. The combination of radial-velocities and astrometry can help to constraint the different orbital parameters of the system (e.g. Pourbaix and Jorissen, 2000).

Given the small expected astrometric motions (of the order of 1 micro-arc-seconds for the best cases)[3], current technology still did not allow to detect from scratch a planet orbiting another star using the astrometric method. The only existing detections are of planets or brown-dwarves firstly detected using

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[3] For example, a Jupiter-like planet in a 10 yr period orbit around a solar-mass star located 10 pc from us, induces an astrometric motion of only 440 micro-arcsec.

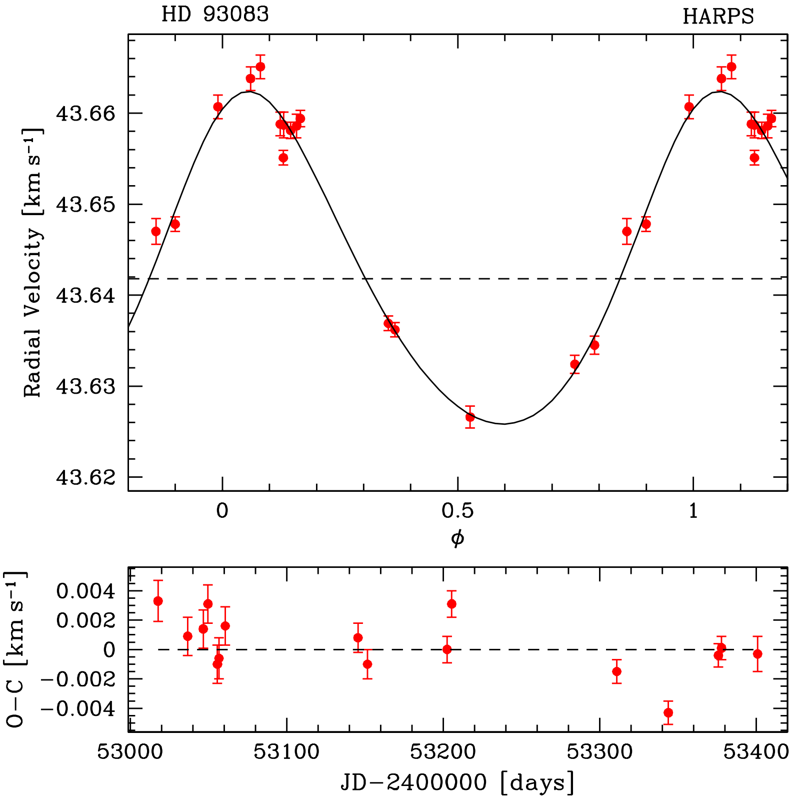

Fig. 2. Periodic radial-velocity signal induced on HD 93083 by the presence of a planet with a mass similar to that of Saturn in a 143-days period orbit (almost circular, with e=0.14). From Lovis et al. (2005).

the radial-velocity technique (e.g. Benedict et al., 2006, see also Fig. 1).

As we can see from equations 1 throught 3, the semi-major axis of the astrometric motion of the star around the center-of-mass of the star-planet system is proportional both to the mass of the companion and to its orbital period. This means that the astrometric technique is most sensitive to long period companions. As we shall see below, this makes this method complementary to the radial-velocity technique. As this latter, however, it is mostly sensitive to de detection of planets around lower mass stars.

Although less problematic than the radial-velocity technique, some limitations to this technique may also be induced by the stars themselves, and in particular for the most active young stars. The existence of stellar spots may induce variations in the photocenter of the image, causing the measurements of spurious astrometric motions (Lanza et al., 2007). These effects can be minimized if we observe in the near-IR, where the contrast between spotted and non-spotted regions in the stellar photosphere is smaller.

Another technique used to search for the stellar motion induced by an orbiting planet is based on the measurement the star's radial-velocity (RV – in the direction of the line of sight). The velocity wobble (RV semi-amplitude) expected for a star of mass M_1 orbited by a planet of mass M_2 can be shown to be:

$$K_1 = 212.9\,(\frac{M_1}{P})^{1/3}\,\frac{q}{(1+q)^{2/3}}\,\frac{\sin i}{\sqrt{1-e^2}} \quad [km\,s^{-1}] \tag{4}$$

where $q = M_2/M_1$, and i is the inclination of the orbital axis with respect to the line of sight. In this equation, the masses (M_1 and M_2) are expressed in solar masses, and the orbital period (P) in days.

The radial velocity of the star can be measured from the Doppler shift using high-resolution spectroscopic measurements. The biggest challenge of this technique is that one needs to measure the stellar velocity with a very high-precision. From equation 4 we can derive that the semi-amplitude K_1 of a star induced by the presence of a Jupiter-like planet (with a mass of $318\,\mathrm{M}_\oplus$ and an orbital period of ∼12 yr) is only $\sim 13\,m\,s^{-1}$, while for an Earth-like planet this value decreases to a mere $\sim 8\,cm\,s^{-1}$.

In the non-relativistic form, the Doppler equation is expressed as:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c} \tag{5}$$

where c is the speed of light, λ is the reference wavelength (at zero velocity – typically the reference wavelength of an absorption spectral line), $\Delta\lambda$ is the wavelength shift observed, and v is the radial velocity. From this equation we can see that in optical wavelengths these small amplitudes translate to values of $\Delta\lambda \sim 10^{-4}$Å. For comparison, a typical high-resolution spectrograph (with a resolution $R=\lambda/\Delta\lambda = 50\,000$) is able to resolve two adjacent wavelengths separated by ∼0.1Å.

To circumvent this problem, two main aspects must be taken into account. First, the typical spectrum of a solar-type star has thousands of well defined absorption lines. Using this information in a statistical way (e.g. using a cross-correlation technique – Baranne et al., 1996) we will be able to achieve the necessary precision. But this is not enough if the spectrograph itself is not stable, or if we cannot control the instrument drifts as a function of time. An accurate way to measure and control the wavelength-to-pixel calibration is needed. This is usually achieved using the spectrum of a calibration lamp that is obtained in simultaneous with the target spectrum (e.g. Baranne et al., 1996; Mayor et al., 2003), or using a gas cell whose spectrum is superposed with the spectrum of our star (e.g. Campbell et al., 1988; Butler et al., 1996).

For reference, currently the most accurate RV instrument for planet searches is the HARPS spectrograph (Mayor et al., 2003), which is able to achieve a long-term precision better than $1\,\mathrm{m\,s^{-1}}$.

One immediate limitation of the RV technique is that we are only able to measure the projected radial-velocity, i.e., the component of the radial-velocity in the direction of the line-of-sight. This implies that we can only estimate the "projected mass" of the companion responsible for the observed stellar wobble, i.e., its minimum mass ($M_2 \sin i$). Fortunately, it can be shown that for orbits randomly oriented in space it is much more likely to have a $\sin i$ close to unity. This means that the minimum masses obtained are statistically very close to the real masses (see e.g. Jorissen et al., 2001). The unambiguous determination of the true mass is however only possible if a value for the orbital inclination is obtained (e.g. through an astrometric detection, a transit measurement or, in the case of very young planetary systems, if the disk inclination if measured).

As for the astrometric technique (where only the stellar position is measured), with RV we are only able to measure the stellar velocity, since the spectrum of the planet is too weak when compared to the stellar spectrum. Although recent developments in infra-red spectroscopy may change this situation, for the moment only K_1 is observed for the several systems discovered. For the so-called spectroscopic binary stars, we can measure both K_1 and K_2. It can be shown that $K_1/K_2{=}M_2/M_1$, meaning that the knowledge of M_1 will immediately give us the "real" mass for the companion.

In Fig. 2 we show a typical radial-velocity curve of a star induced by the presence of a planetary companion. In practice, the orbital parameters of the system (semi-amplitude K, orbital period P, eccentricity e, the angle between the periastron and the line-of-nodes ω, the periastron passage time T_0, and the systemic radial-velocity V_γ) can be obtained from a fit of the observed points[4]. From these, $M_2 \sin i$ can be obtained directly from the so called mass function:

$$f(m) = \frac{(M_2\,\sin i)^3}{(M_1+M_2)^2} = 1.036\,10^{-7}\,K_1^2\,(1-e)^{(3/2)}\,P \quad [M_\odot] \tag{6}$$

where the semi-amplitude K_1 is given in $\mathrm{km\,s^{-1}}$, and the orbital period in days.

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[4] We will not present here the necessary equations needed to fit the radial-velocities; we point to Hilditch (2001) for details.

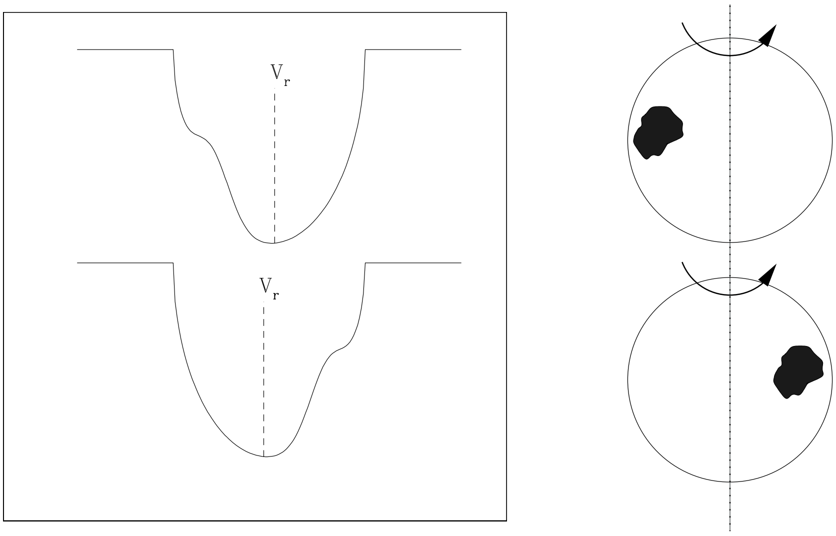

Fig. 3. Figure illustrating the effect of a stellar dark spot in the shape of the spectral lines. Here the effect is exaggerated for clarity reasons.

As for the astrometric technique, the RV method has its own limitations. It is well known that intrinsic stellar features, like non-radial pulsation, inhomogeneous convection, or spots may be responsible for the detection of radial-velocity variations (Brown et al., 1998; Saar and Donahue, 1997; Santos et al., 2000; Paulson et al., 2002; Tinney et al., 2002). These situations can prevent us from finding planets, if the perturbation is larger than the orbital radial-velocity variation, or even give us false candidates, if they produce a periodic and stable signal over a few rotational periods.

In Fig. 3 we illustrate the effect of a dark spot in the spectral lines of a rotating star. When obtaining the spectrum of a star we are measuring the integrated spectrum of the whole stellar disk, i.e., the sum of the spectra at each position in the stellar disk, each one with its own Doppler shift. The presence of a dark spot implies, in a rough approximation, that light with a given Doppler shift (corresponding to the velocity of the spectra at the position of the spot) will not be added to the total spectrum. In other words, this will induce a change in the line-profiles, and consequently affect the measurement of the position of the spectral lines.

A good example of this effect is the periodic radial-velocity signal observed for the dwarf HD 166435, that was shown to be due to a spot rather than to the presence of a planet (Queloz et al., 2001).

The presence of unknown stellar blends can also induce spurious radial-velocity signals, which can "simulate" the presence of a planetary companion in the case of triple systems. An example is given by HD 41004 in which the moving spectrum of a faint spectroscopic binary companion induces a planetary-type signature on the blended spectrum of the primary star (Santos et al., 2002).

Finally, the acoustic modes of solar-type stars as well as atmospheric granulation and turbulence motions can also cause significant noise in the measurements, specially if we are willing to detect very low mass planets, that induce radial-velocity amplitudes of the order of a few $\mathrm{m\,s^{-1}}$ (Bouchy et al., 2005a; O'Toole et al., 2007). To circumvent this effect, long exposures ($\sim$15 min) are usually taken to average out the solar-type acoustic modes (e.g. Bouchy et al., 2005a). These modes have typical periods of the order of 5 minutes.

Given all these effects, diagnostics have to be applied to confirm that the RV signal observed is due to the presence of a planet and not to some of the above mentioned effects. Accurate photometry gives the possibility to measure the existence brightness variations typical of the presence of spots or stellar pulsation (this latter only important for giant stars). Measurements of the line-asymmetries through bisector analysis (e.g. Gray, 1992; Hatzes, 1996; Queloz et al., 2001) is also used, allowing to probe the existence of spots or stellar blends. An analysis of the chromospheric activity level of the star (e.g. Santos et al., 2000) is also important. In general these methods are able to guarantee a good diagnostic.

These facts also imply that the RV technique is applicable mostly for main sequence late-type stars (F, G, K, and M dwarfs). Young active objects, as well as early-type fast rotating stars (with few spectral lines and/or rotationally broadened lines), are usually not good targets for planet searches using RV techniques. Although a few exceptions exist (e.g. Setiawan et al., 2003; Galland et al., 2006), most of the RV surveys have thus concentrated their efforts in looking for planets around F-G-K- and M dwarfs.

2.3 Photometric transits

When a planet crosses the stellar disk as seen from us, it will block part of the star's light. This phenomenon, called a transit, can be observed if the orbital axis of the planet is closely perpendicular to our line of sight (see Fig. 4).

For a given system, we can compute that the geometric probability (P) that a full transit will occur can be expressed by:

$$P = \frac{R_{star}}{a} \tag{7}$$

where R_{star} and a are the stellar and orbital radius, respectively. This formula is valid for the case of a circular orbit. From this equation we can see that the transit technique is more sensitive to short period planets. While for a 3-days short period orbit hot-jupiter P is close to 10%, for a planet at 1 AU from its parent star (Period close to 1 year) P goes down to a mere 0.5%.

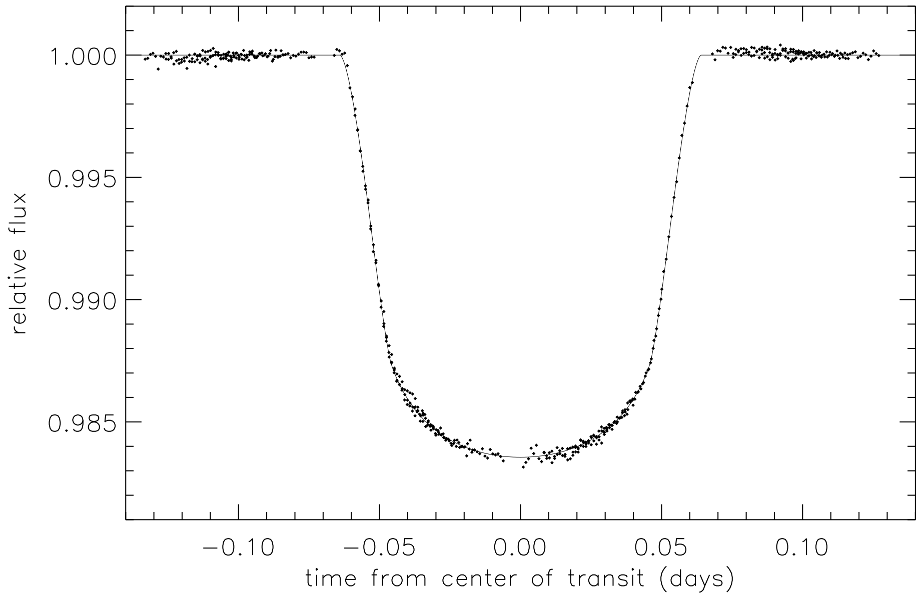

Fig. 4. Transit signal of the planet HD 209458 b in front of its parent star. From Brown et al. (2001).

If a transit event is observed, the expected luminosity variation can be derived to be of the order of:

$$\frac{\Delta L}{L} = (\frac{R_{planet}}{R_{star}})^2 \tag{8}$$

For a Jupiter like planet, $R_{planet} \sim 0.1\,R_{star}$, inducing thus a photometric variation of the order of 1%. Much lower values are expected for transits of Neptune or Earth like planets.

Finally, in the case of an equatorial transit (best case scenario), the transit duration can be derived from:

$$t = 13\,R_{star}\,(\frac{a}{M_{star}})^{1/2} \tag{9}$$

where R_{star}, M_{star}, and a are expressed in solar units and AU, respectively. Usual transit times are of a few hours for short period planets.

As for the previous cases, the transit technique has its own limitations. In particular, it is known that the measurement and modeling of a transit light curve "only" gives us the ratio of the stellar-to-planetary radius (see e.g. Mandel and Agol, 2002). Unfortunately, for objects with masses below ∼100 times the mass of Jupiter, the mass-radius relation is extremely flat. The photometric signal due to the transit by a Jovian planet or a brown-dwarf are thus indistinguishable (see e.g. Pont et al., 2005b). The dynamical confirmation of the mass of the companions thus needs to be done, usually using RV observations. Interestingly, once the photometric transit and the RV observations are available, we can almost completely characterize the system (we only need spectroscopic observations to constraint the stellar properties), and obtain accurate values for the radius, mass, and density of the planet.

Other phenomena are also able to induce photometric signals that can mimic the ones expected from a planetary transit. For example, several candidates have been announced by different photometric transit surveys like OGLE (e.g. Konacki et al., 2003), TrES (e.g. Alonso et al., 2004), XO (McCullough et al., 2006), HAT (e.g. Bakos et al., 2007b), and WASP (e.g. Cameron et al., 2007). One of the most prolific up to now is the OGLE (Optical Gravitational Lensing Experiment) campaign, which announced about 200 possible transiting planets (Udalski et al., 2002a,b). These new detections stimulated intensive follow-up observations to detect the radial-velocity signatures induced by the orbiting body. Surprisingly these studies revealed that most of the systems were rather eclipsing binaries of small stars (e.g late M dwarfs) in front of F-G dwarfs, eclipsing binaries of main sequence stars in front of giants or in blended multiple stellar systems (triple, quadruple), grazing stellar eclipses, or simply false transits, all mimicking photometric planetary transits (e.g. Bouchy et al., 2005b; Pont et al., 2005a). Finally, only 7 candidates have up to now been confirmed as planets in transit among the OGLE candidates. This problem may be particularly important for deep photometric transit surveys, where RV follow-up observations are more difficult. For example, a recent work using the HST is yielding 16 planet candidates (Sahu et al., 2006), some with unprecedented very short period orbits ($<$1 day). However, except in maybe one case, no RV confirmation is possible for these very faint stars ($V \geq 20$).

3 Planet search results

Prior to 1995, all our understanding of planet formation was based on studies of one system, the solar system. The failure of our theories to explain the diversity of the over 200 exoplanets has dramatically shown the necessity for further observational guidance. In the case of the exoplanets, this guidance is provided by a careful statistical analysis of the distribution of masses, periods, orbital eccentricity as well as of the chemical properties of the host star.

In this section we will briefly describe the major results regarding the statistical analysis of the properties of the extra-solar planets. For a more thorough description we refer to Udry and Santos (2007) and (Eggenberger and Udry, 2007). To put the discoveries into context, we first briefly describe in rough lines the two major planet formation models.

Two major giant planet formation models currently exist. The most traditional of them is the so called core accretion model. In this model, a solid core is first formed by the accretion of planetesimals. As the core grows, it eventually becomes massive enough to gravitationally bind some of the nebular gas thus surrounding itself by an envelope. The subsequent evolution of this core-envelope structure has been studied in detail (Pollack et al., 1996) and it was shown that the solid core and the gaseous envelope grow in mass, the envelope remaining in quasi-static and thermal equilibrium. During this phase, the energy radiated by the gas is supplied by energy released from the accretion of planetesimals. As the core mass reaches a critical value (of the order of $15\,M_\oplus$ at 5 AU, but depending on different physical parameters, such as the solid accretion rate onto the core), radiative losses can no longer be offset by planetesimal accretion and the envelope starts to contract. This increases the gas accretion rate which in turn raises the radiative energy losses causing the process to run away leading to the very rapid build up of a massive envelope.

This model implies that a core with a critical mass must be formed before the disappearance of the disk. The lifetime of proto-planetary disks is though to be of the order of 1-10 Myr (Haisch et al., 2001). Because this lifetime is of the same order, if not smaller, than the planet formation time-scale, a fast growth of the core is essential. Fast growth is thought to occur preferentially beyond the so-called ice line, the point where the nebula becomes cold enough for ices to condensate thereby maximizing the density of solids available for accretion. In solar nebula models, this was thought to occur around or beyond roughly 3 AU and therefore explained the dichotomy between the inner and outer solar system. It has recently been shown that if growing cores are allowed to migrate (Rice and Armitage, 2003; Alibert et al., 2004) they accrete much faster and therefore giant planets can form well within inferred disk lifetimes.

Another way to speed-up giant planet formation is to form them directly from the gravitational fragmentation and collapse of a proto-planetary disk (Boss, 2002). Owing to the numerical difficulties involved in following this process, there are, however, still a number of open issues. For example, the formation and survival of bound structures is still being debated because most calculations so far have used an isothermal equation of state and/or inadequate resolution. Furthermore, the bound structures formed are always significantly more massive than Jupiter, therefore it is not yet clear whether smaller mass giant planets (a Saturn for example) can be formed by this mechanism. Finally, it remains to be seen if such a formation mechanism can account for the peculiar composition and structure (enrichment in heavy elements compared to solar and size of solid core) of Jupiter and Saturn.

The existence of giant planets with orbital periods of less than ~10 days, the so called "hot-jupiters", poses important difficulties to giant planet formation scenarios. The most important is related to the high temperatures in these regions which either prevent the condensation of enough solids to form a core capable of accreting several hundred earth's masses of gas during the lifetime of the disk or simply inhibit direct collapse. To circumvent this, migration of planets over relatively large distances is often invoked. Close-in planets may have formed at large distances and then migrated inward. Thus, the existence of "hot-Jupiters" has forced on us the concept that the current locations of planets may have little to do with their birthplaces.

Migration can be due to several physical processes such as gravitational scattering in multiple systems (Marzari and Weidenschilling, 2002) as well as gravitational interactions between the gaseous and/or the planetesimal disk and the planet (Lin et al., 1996; Murray et al., 1998). Both these mechanisms must necessarily occur and interactions between an embedded planet and a gaseous disk had been discussed before the discovery of the first exoplanet (Goldreich and Tremaine, 1980). The question is not whether migration takes place or not, but rather what is its direction and amplitude.

Two types of migration modes have been identified depending on whether the planet is massive enough to open a gap in the disk (type II migration) or not (type I migration) (Lin and Papaloizou, 1986; Ward, 1997; Tanaka et al., 2002) – (see Papaloizou and Terquem, 2006, for a more detailed definition of the different migration regimes). All these models conclude that planets are migrating mostly inward, over large distances and fast. In fact, migration timescales obtained so far are so short (especially for type I migration) that, in almost all cases, planets should not survive but fall into their host star (Trilling et al., 1998; Alibert et al., 2004). Because planets are actually observed, in large numbers, and at various distances to their stars, two conclusions can be drawn: our migration theory is still incomplete or core accretion is not the way most planets form. Since new ideas for slowing down migration are emerging (Ida and Lin, 2004a), and since core accretion models based on a slower rate are capable to meet quantitative tests (Alibert et al., 2005), we rather favor the first hypothesis.

Evidence of a mechanism halting the inward migration of planets at short distances may be deduced from the observed overabundance of planetary companions with periods around 3 days, while for smaller orbital periods only a few cases exist (Gaudi et al., 2005). Note that this result is in contrast with the period distribution of stellar companions for which periods much shorter than 3 days exist.

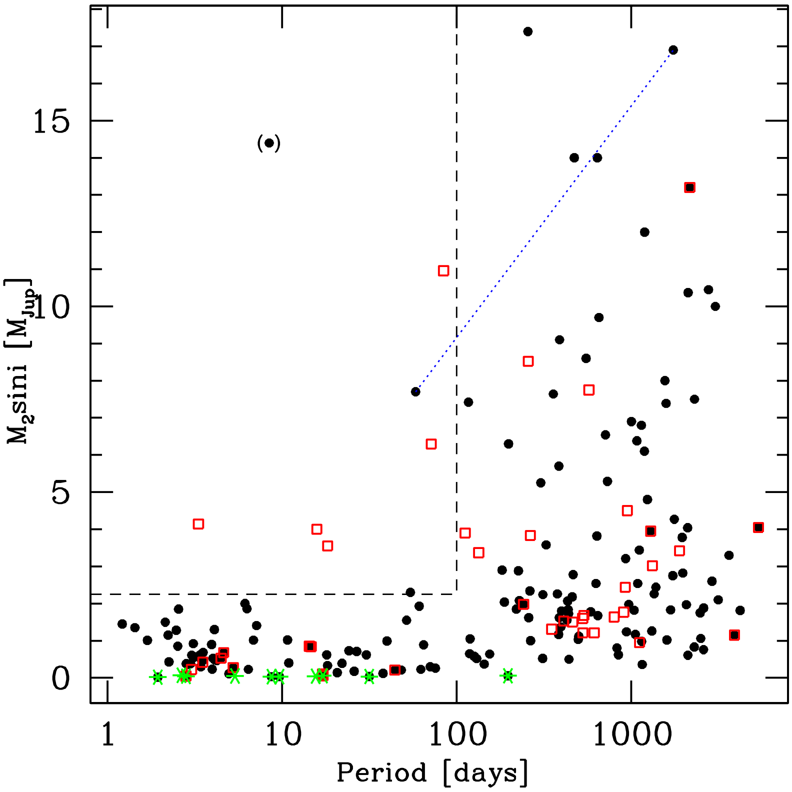

Fig. 5. Period-mass distribution of known extra-solar planets orbiting dwarf stars. Black dots are for planets around single stars, red squares for planets in binaries, and stared symbols for "solid" planets. Dashed lines are limits a 2.25 M_{Jup} and 100 days. The dotted line connects the 2 "massive" components orbiting the star HD 168443.

The physical mechanism responsible for halting and parking the planet at short distances from the host star is still being debated. Possible mechanisms include the existence of a central cavity in the disk, tidal interaction with a fast spinning host star or even Roche lobe overflow (Trilling et al., 1998). Another possibility is that planets venturing closer are photo-evaporated by the radiation field emitted by the host star thus becoming too small to be detected or vanishing altogether (Baraffe et al., 2004). The case of the few new OGLE transiting planets (Konacki et al., 2003; Bouchy et al., 2004) having orbital periods of less than 2-days, may in this context be interpreted as the tail of the short period planets distribution (Gaudi et al., 2005).

While these stopping mechanisms are relevant at short distances, they do not explain why giant planets are found at intermediate distances (e.g. with periods around 1 year) nor why Jupiter, for example, has apparently remained beyond 5 AU. In fact, recent extensions of the core-accretion models to include disk evolution and planetary migration suggest that planets essentially migrate until the disk disappears (in fact until the disk becomes much less massive

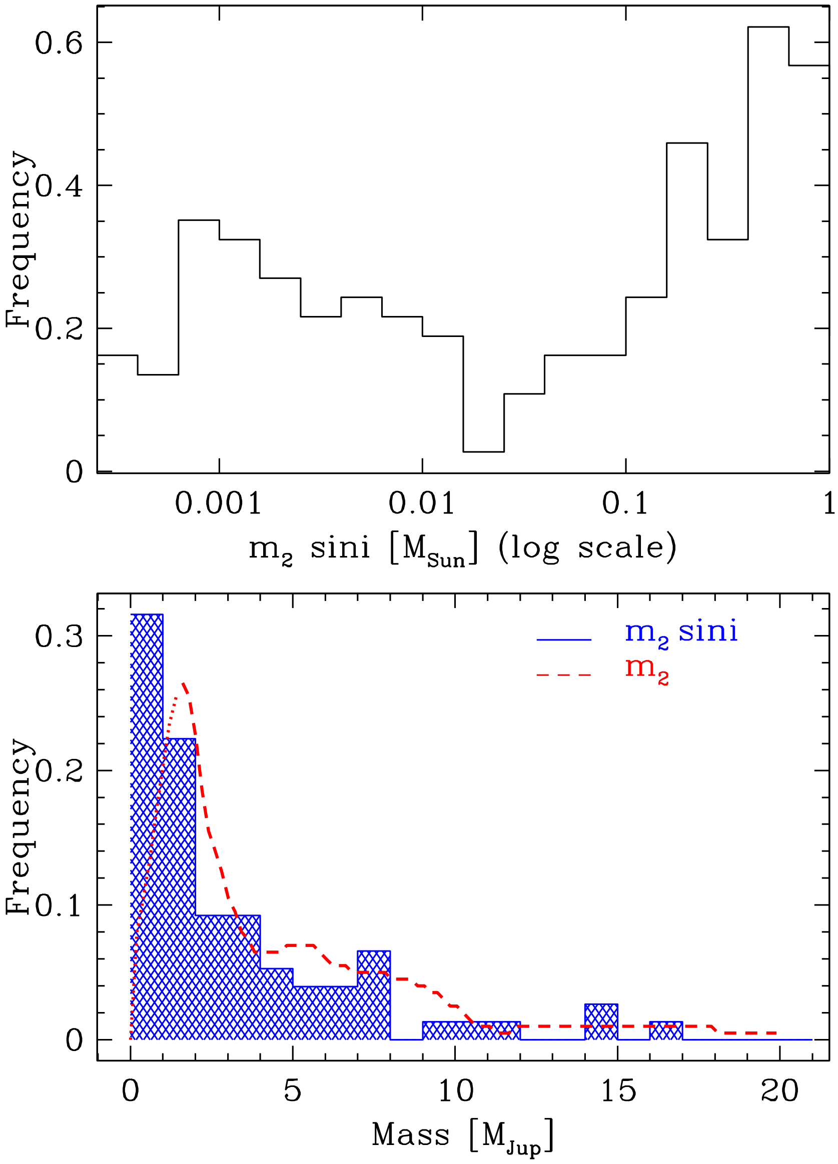

Fig. 6. Mass function of companions to solar-type stars in *log* (top) and linear (bottom) scales. In the lower panel, the dashed line represents the result of a statistical deconvolution of the observed distribution in order to take into account the effect of the orbital inclination. As in (Jorissen et al., 2001).

than the planet Ida and Lin, 2004a; Alibert et al., 2005). In this picture, the diversity results from the distribution of parameters such as the disk masses, lifetimes, disk processes, photo-evaporation, and number of planets formed. Unfortunately, none of these parameters is precisely known, and it may even be that planetary formation itself is providing a feed-back mechanism (Sari and Goldreich, 2004).

The observed mass-period distribution of planetary companions may be telling us something about these issues (Cumming et al., 1999; Udry et al., 2003). There seems to be a paucity of high-mass planetary companions orbiting on

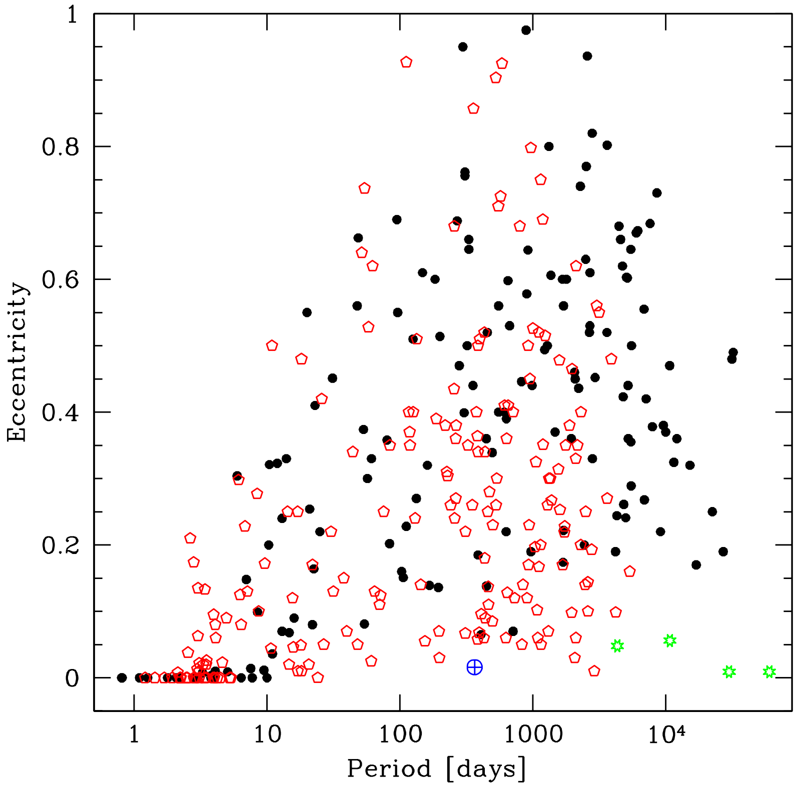

Fig. 7. Period-eccentricity diagram for the sample of known exoplanets (red open pentagons) in comparison with stellar binaries (black dots). The Earth and giant planets of the Solar System are also indicated as well.

short period (lower than ∼40-days) trajectories (Fig. 5). Current statistical analysis suggests that the migration of a planet may be strongly related to its mass, or even to the presence of other stellar companions (Zucker and Mazeh, 2002; Udry et al., 2003). Interestingly, this correlation may not be valid for planets in multiple stellar systems, suggesting that the presence of a stellar companions may change the migration rates.

The analysis of the mass distribution of short period (below ∼3000 days) companions to solar-type stars indicates that although the radial-velocity technique is more sensitive to massive companions, the frequency of discovered planets increases as a function of decreasing mass (Jorissen et al., 2001) (see Fig.6). Furthermore, this distribution falls to a value close to zero for masses between about 10 and 20 times the mass of Jupiter. From 20 to 60 Jupiter masses there is then a scarcity of companions to solar-type stars. This gap, usually called the brown dwarf desert (see e.g. Halbwachs et al., 2000) separates the lower mass planetary companions from their higher mass stellar counterparts, including brown-dwarfs, considered to be failed stars. Together with the shape of the mass distribution this suggests a different formation mechanism between low-mass companions to solar-type stars and planetary

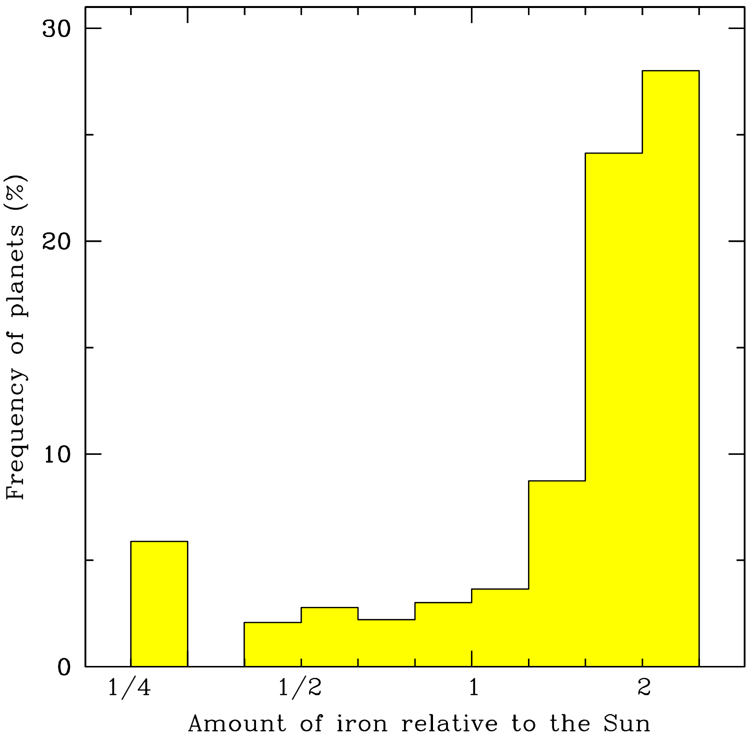

Fig. 8. Percentage of stars having a planetary companion as a function of stellar metallicity. From (Santos et al., 2004c).

systems.

The analysis of the orbital eccentricity distribution also indicates that the measured values range from about 0 to more than 0.9, a range similar to the one found in binary stars (see Fig. 7). However, recent analysis (Halbwachs et al., 2005) suggest that planetary systems have on average a lower eccentricity than multiple stellar systems. While this might be interpreted as the signature of a different formation mechanism, it is worth pointing out that these high eccentricities cannot be accounted for in the standard formation model of giant planet formation. Eccentricity pumping mechanisms such as interactions in multiple systems (Rasio and Ford, 1996; Murray et al., 2002), or the interactions between the planet and the disk of planetesimals (Murray et al., 2002) have to be invoked to explain these high eccentricities.

3.3 The stars hosting planets

The study of the stars hosting giant planets has also found an unexpected correlation whose importance to planet formation models is now recognized.

Gas giant host stars have, on average, a higher metal content than the stars with no planetary companions detected (Gonzalez, 1998; Santos et al., 2001). In other words, these stars have higher ratio of heavy elements-to-hydrogen than the one observed in average solar-type field stars. The most recent studies have shown that the observed trend cannot be due to any sampling or observational bias (see Santos et al., 2004c, and references therein). More than 20% of stars with metallicity greater than two times the solar metallicity harbor a planet, while only about 3% of stars with solar metallicity have a giant planet (Santos et al., 2001; Reid, 2002; Santos et al., 2004c; Fischer and Valenti, 2005) – see Fig. 8. However, this does not imply that giant planets cannot be formed around more metal-poor stars, but rather suggests that the probability of formation in such a case is significantly lower (Ida and Lin, 2004b). Indeed, there is a hint that for lower metallicity values, the frequency of planets may remain relatively constant (Santos et al., 2004c) as a function of the stellar metallicity. If this reflects the presence of two different regimes, or a low metallicity tail is currently under debate and more data will be needed before this question can be answered.

While pollution of the star by infalling planetary material has been suggested to explain the higher metallicities (Gonzalez, 1998; Vauclair, 2004; Pasquini et al., 2007), it is now believed that the stellar surface abundance is a relic of the original elemental abundance in the gas clouds having given birth to the stars and the planets (Pinsonneault et al., 2001; Santos et al., 2003). In other words, this implies that giant planetary formation, at least for the kind of planets that have been discovered so far, is far more efficient in a metal-rich environment. Alternatively, the metallicity could be increasing the migration rates of the giant planets. In such a case we could be simply discovering those planets with periods that are relatively short, and thus, those bodies orbiting metal-rich stars. This possibility receives some support from the possible (weak) correlation found between the stellar metal content and the orbital period of the planets (Gonzalez, 1998; Sozzetti, 2004). However, not only the observational evidence is weak, but also recent models suggest that such an influence is probably not strong enough to effectively change the migration rates (Livio and Pringle, 2003), which are already much faster than the traditional planet formation process itself.

More heavy elements should, in principle, lead to faster core growth and therefore to an easier formation of giant planet in the core accretion scenario. Models claiming to explain quantitatively this correlation have been proposed (Ida and Lin, 2004b). In the direct collapse model, the connection would need to be a more subtle one, in which metallicity affects the ability to collapse, i.e., to radiate energy. So far, calculations (Boss, 2002) indicate that collapse is insensitive to metallicity. Therefore, in this formation scenario, the observed correlation between stellar metallicity and likelihood to host a planet would have to be due to pollution by ingested planetary material. As a consequence, it seems that current results support core-accretion as the main process leading to the formation of the now discovered planets. Disk instability is, however, not excluded as a viable way to form planets, in particular around metal-poor stars.

Interestingly, the metallicity-planet correlation may not exist for stars hosting low mass (Neptune-like – see Sect.3.5) planets (Udry et al., 2006). The Neptune-mass planets found so far have a rather flat metallicity distribution. This observational fact is supported by recent theoretical work. Ida and Lin (2004a) and Benz et al. (2006) have shown that planets in the Neptune-mass regime should be common around stars with a wide range of metallicities. Lower-mass planets may even exist preferentially around metal-poor stars (Benz et al., 2006). This lack of correlation is roughly explained by the fact that following the core-accretion model, decreasing the metal content of a star (and of its disk) will increase the formation timescale of the cores. They may then not achieve enough mass to start a runaway accretion of gas, thus keeping a mass of the order of a few times the mass of the Earth.

Recent results also suggest a lack of metallicity correlation for evolved intermediate-mass stars hosting planets (Pasquini et al., 2007; da Silva et al., 2006a) – see however discussions in Johnson et al. (2007), Hekker and Meléndez (2007) and Santos et al. (2007). The cause for this is not clear, and may be related to the positive correlation that is found between stellar mass the the frequency of planets (Lovis and Mayor, 2007; Johnson et al., 2007).

3.4 Transiting planets: probing the planet structure

So far, most of the known extra-solar planets have been unveiled by the use of the Doppler radial-velocity technique. Alone, this only gives us information about the orbital parameters of the planets and their minimum masses, and no information is given about the planetary physical properties, like its real mass, radius, and mean density. The detection of a planet using the photometric transit method, however, can give us the possibility to study these quantities. Until recently, however, in only a few cases it had been possible to measure the small dimming of the stellar light as the planet crossed the stellar disk.

Fortunately, some major planet-search programs using the photometric transit technique start now to deliver interesting results, giving a new breath to the study of exoplanets. In about 25 cases the planetary nature was confirmed by follow-up radial-velocity measurements (Charbonneau et al., 2000; Sato et al., 2005; Bouchy et al., 2005b; Konacki et al., 2003; Bouchy et al., 2004; Pont et al., 2004, 2005a; Alonso et al., 2004; McCullough et al., 2006; O'Donovan et al., 2006, 2007; Bakos et al., 2007a,b; Cameron et al., 2007; Burke et al.,

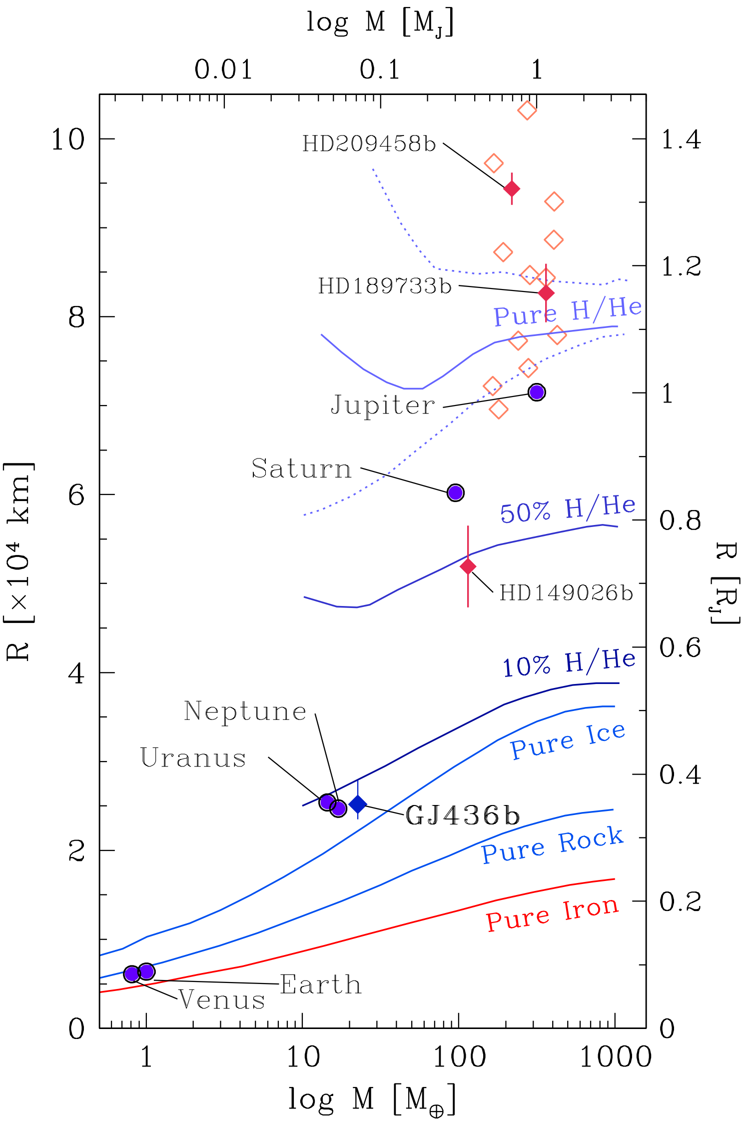

Fig. 9. Planetary mass-radius diagram comparing the position of Solar System planets, transiting hot Jupiters (diamonds), and the Neptune-like GJ 436 b. The lines indicate the position of the Fortney et al. (2007) models for different compositions: pure iron, pure silicate, pure water ice (with thermal profiles from Solar System planets), and models for irradiated planets at 0.1 AU from a Solar-type star with a fraction of 10%, 50% and 100% of Hydrogen/Helium. The dotted lines show the models for a cold (a = 10 AU) and very hot (a = 0.02 AU) pure H/He gas giant. From Gillon et al. (2007).

2007). The today's known transiting extra-solar giant planets are finally giving us information about the physical properties of giant planets orbiting other stars, and opening the possibility to confront the observed properties with those predicted by theoretical models (Baraffe et al., 2005; Guillot, 2005).

Complementary follow-up observations of the transits have further allowed to access the atmospheres of these worlds, giving important clues about the physics of their atmospheres (Charbonneau et al., 2002). The planet orbiting HD 209458 was found to have an exosphere, with carbon and oxygen atoms being hydrodynamical carried by the evaporating hydrogen atmosphere (Vidal-Madjar et al., 2003, 2004). The detection in the infra-red of the anti-transit of the planets orbiting HD 209458, HD 189733 and TrES-1 (Charbonneau et al., 2005; Deming et al., 2005, 2006), as well as of phase temperature variations (or their absence) (Harrington et al., 2006; Knutson et al., 2007), provide us with the possibility to understand the temperature distribution on the planet. More recently, a clear water vapour signature was detected in the atmosphere of HD198733b (Tinetti et al., 2007).

The new detections have also raised a lot of scientific challenges and questions. For example, the planets have a large diversity of mean densities, some of them anomalously high. Examples are the planets orbiting HD209458 (Charbonneau et al., 2000) and the recently announced planet HAT-P-1b (Bakos et al., 2007b). This lower density is difficult to explain by the models of planetary structure, and need the inclusion of more detailed studies (e.g. Guillot, 2005; Mardling, 2007). Curiously, the planets that have shorter periods also have the highest masses (Mazeh et al., 2005; Cameron et al., 2007). This puzzling observation could be the consequence of mechanisms such as thermal evaporation (Baraffe et al., 2004, 2005; Lecavelier Des Etangs, 2007) or Roche limit mass transfer (Ford and Rasio, 2006), although a clear explanation does not exist yet.

Recent studies indicate the existence of a correlation between stellar metallicity and planetary structure (Guillot et al., 2006), a trend that if confirmed may give important constraints into the processes of planetary formation and evolution.

Finally, a word to mention that in some cases the measurement of the spectroscopic transit, through the Rossiter-McLaughlin effect, allowed to verify that the orbital and stellar rotational axis are nearly aligned (e.g. Queloz et al., 2000; Giménez, 2006). This is what is expected from a planet formed in a circumstellar disk.

3.5 Neptunes and Super-Earths

Most of the detected planets are gaseous giants similar to our own Jupiter, with typical masses of a few 100's of Earth masses. Lower mass planets are difficult to detect because the induced radial-velocity variations are smaller. However, in the past three years, several planets with masses in the Uranus-Neptune range or lower ($\leq 20\,\mathrm{M}_\oplus$) have been detected (e.g. Santos et al., 2004b; McArthur et al., 2004; Butler et al., 2004; Rivera et al., 2005; Bonfils et al., 2005; Vogt et al., 2005; Udry et al., 2006; Lovis et al., 2006; Udry et al., 2007). The lowest mass planet in this list orbits the M dwarf Gl 581 (Udry et al., 2007), and has a minumum mass of $\sim 5\,\mathrm{M}_\oplus$. Because of their small masses and locations in the system, close to their parent stars, these "light" planets may well be composed mainly of a large rocky/icy core (e.g. Brunini and Cionco, 2005; Alibert et al., 2006). It is possible that they either lost most of their gaseous atmosphere or simply formed without accumulating a substantial one (e.g. Lecavelier Des Etangs, 2007; Baraffe et al., 2005, 2006; Hubbard et al., 2007).

The discovery of very low-mass planets so close to the detection threshold of radial-velocity surveys, and over a short period of time, suggests that this kind of objects may be rather common. Moreover, at larger separations (2-3 AU), the microlensing technique is finding similar mass objects (the lightest with a mass of $5.5\,\mathrm{M}_\oplus$, Beaulieu et al., 2006), showing that smaller mass planets can be found over a large range of separations. This is in good agreement with the latest Monte Carlo simulations of accretion-based planet formation models predicting large numbers of "solid" planets (Ida and Lin, 2004a, 2005; Alibert et al., 2004; Benz et al., 2006).

Recently also, the first transit by a Neptune-mass planet has been detected. The planet, orbiting the star Gl 436, was firstly discovered using the radial-velocity method (Butler et al., 2004). A subsequent photometric campaign showed the transit signature (Gillon et al., 2007). The data shows that this planet has the expected radius for a Neptune-like planet, compatible with the structure composed of an icy core surrounded by a possible thick atmosphere (see Fig. 9).

4 Towards the future

As seen in the previous sections, the study of the statistical properties of the exoplanets, as well as of their host stars, is now providing important clues on the processes of planetary formation and evolution. Slowly, we are building a new paradigm. And from this point of view, a whole new window is expected to be open during the next few years, as new and more precise surveys will produce their first results. These will increase dramatically the number and diversity of known planets, and give us more information about the existing ones.

An important learning from the past few years is that the radial-velocity technique has not reached its "limits" yet, in the domain of exoplanets. In fact, the future of radial-velocities is still bright. Current surveys, including

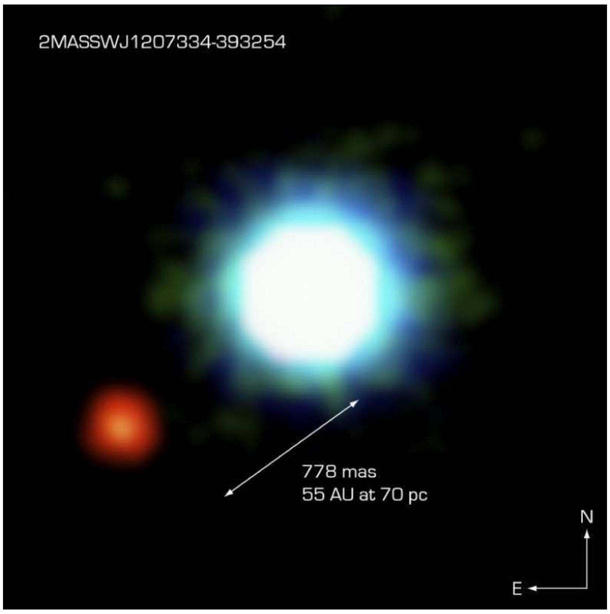

Fig. 10. Adaptive-optics image of a brown-dwarf and its companion. The two stars in the system have masses of 25 and 5 times the mass of Jupiter. Although the companion has a mass within the giant planet range, the small mass of the primary and the large separation of the two objects seems to imply that it is not a planet; we are rather observing a binary brown-dwarf. From Chauvin et al. (2004).

between 3000 and 4000 stars, will continue to increase the number of known exoplanets. Several dozens are expected to be announced in the next few years. Instruments like HARPS (Pepe et al., 2002), capable of achieving the $1\,\mathrm{m\,s^{-1}}$ precision or better, as well as new projected high-resolution spectrographs for the new generation of Extremely-Large Telescope, will certainly play an important role. Amongst other things, these will give the opportunity to find lower and lower mass planets, explore the formation of giant planets at the low end of the main-sequence, and find systems more similar to our own Solar System. In some systems composed of more than one giant planet, the continuous follow-up of the radial-velocity measurements will unveil trends that are caused by planet-planet interactions (e.g. Rivera et al., 2005). With time, and using dynamical models, it will be possible to obtain precise estimates for the masses and orbital inclinations of the two planets.

Recent discoveries indicate that a population of Neptune- and Saturn-mass planets remains to be discovered below 1 AU. The increasing precision of the radial-velocity surveys will thereby provide useful new constraints on planet formation theories. With the precision level now achieved for radial-velocity measurements, a new field in the search for extra-solar planets is open, allowing the detection of companions of a few Earth masses around solar-type stars. Very low-mass planets ($< 10\,\mathrm{M}_\oplus$) might be more frequent than the previously found giants.

The threshold of the lowest mass planet detectable by the Doppler technique keeps decreasing. Nobody has explored in detail yet the domain below the $1\,\mathrm{ms}^{-1}$ level. Results obtained with the HARPS spectrograph show that, even if stars are intrinsically variable in radial velocity (at different levels) due to acoustic modes, it is nevertheless possible to reach on short term precisions well below $1\,\mathrm{ms}^{-1}$ by applying an adequate observational strategy. One open issue remains however unsolved: the behavior of the stars on longer time scales, where stellar jitter and spots may impact the final achievable accuracy. In this case, an accurate pre-selection of the stars may help focusing on good candidates and optimizing the observation time. In addition, bisector analysis and follow-up of chromospheric activity indicators, as well as photometric measurements, would allow identifying potential error sources.

Photometric transit searches are also among the most promising techniques. Today, dozens of programs are surveying the skies to look for small-depth eclipses. Candidates have been announced and confirmed using follow-up radial-velocity measurements. Today, the ∼25 known transiting planets are opening a new window to the study of the properties of the exoplanets themselves, like their density or atmospheric composition and structure.

In this domain, further (and higher) expectations are coming from space-based instruments like COROT or Kepler. Out of the Earth's atmosphere, these satellites will achieve a photometric precision better than 0.01%, permitting the detection of transiting earth-sized planets. These discoveries, complemented with high-precision radial-velocity measurements, will give us a chance to obtain the real mass for the planetary companions, and to largely expand the study the properties of the planets themselves. For these small size objects, radial-velocity follow-up measurements are also mandatory to have access to the mass of the transiting companions and then to their mean densities. For a given planetary mass, different compositions (e.g. rocky, icy or gaseous) will produce different transit signals (e.g. Valencia et al., 2006; Fortney et al., 2007). Radial-velocity follow-up thus ascertains the planetary nature of the companions and provides important parameters to constrain planetary atmosphere and interior models. This is important in view of the expected results of the space missions COROT and Kepler that should provide hundreds of transit candidates of various sizes and masses, in the coming years. If one considers a transit signal with known orbital period, measuring its mass is less demanding both on the number and the accuracy of the required radial velocity measurements. For example, a 2 $\mathrm{M}_\oplus$-planet on a 4-days orbit induces a radial-velocity amplitude of about $80\,\mathrm{cms}^{-1}$ that will be possible to detect with only "few" high-precision radial-velocity measurements, provided that the period and phase of the planetary orbit are known in advance. In this context, the most exciting aspect is the opportunity to explore the mass–radius relation down to the Earth-mass domain.

From the astrometric point of view, the expectations are not lower. Instruments like the HST and the VLTI interferometer (with the PRIMA instrument) will give us the possibility to estimate real masses for many of the known planetary systems. An example of such a measurement was obtained by Benedict et al. (2002) for one of the planetary companions orbiting the M-dwarf Gliese 876, previously discovered using radial-velocity techniques (Delfosse et al., 1998; Marcy et al., 1998). Furthermore, space missions like GAIA are expected to completely change the current landscape by adding thousands of new planets or pushing down the detection limits towards very low-mass planets. Given that astrometry is more sensitive to longer period systems (contrary to the radial-velocity method), these projects will also complement the radial-velocity searches, and will help to better cover the period distribution of the detected exoplanets. They will further permit to find planets around targets not easily accessible with radial-velocity surveys, like A or B stars, or T Tauri stars.

With the number of known planets growing, further studies concerning the chemical abundances of planet-host stars will be undertaken. Current radial-velocity surveys are also searching for planets around stars of different metallicities (both metal-rich and metal-poor – Sato et al., 2005; da Silva et al., 2006b; Mayor et al., 2003; Sozzetti et al., 2006), to better constrain the current results. It will also be very interesting to follow the metallicity measurements as different kinds of planets are found (e.g. very low-mass planets or planets more similar to the Solar-System giants). These kind of analysis will also be complemented with abundance studies of other chemical elements in planet-host stars, as well as with the analysis of other stellar physical properties (e.g. stellar mass).

Another important challenge in the field is to directly image a planet orbiting a solar-type star. Current adaptive-optics instrumentation are already giving us the first images of very low-mass companions to close-by young stars (e.g. Chauvin et al., 2004; Neuhäuser et al., 2005) – Fig. 10. The development of a new generation of adaptive-optics systems (e.g. the ESO and Gemini planet finder instruments, SPHERE and GPI, respectively) promises a great improvement in this field.

All the mentioned progresses will permit to better understand the mechanisms leading to the formation of planetary systems like our own, and will thus represent an important step towards the search for life in the universe. Once earth-like planets orbiting in the habitable zone are known, the search for life in these systems will undoubtedly follow. Two similar projects are currently directed towards this specific goal: the space interferometers Darwin (ESA) or the Terrestrial Planet Finder (NASA) missions. Using optical coronography and nulling interferometry techniques, spectroscopic signatures of life are expected to be detected in the atmospheres of these planets. In a very close future humanity has to prepare itself to find out that the whole universe may be teeming with life.

We would like to thank the support from Fundação para a Ciência e a Tecnologia (FCT, Portugal), in the form of a grant (POCI/CTE-AST/56453/2004). This work was supported in part by the EC's FP6 and by FCT with POCI2010 and FEDER funds, within the HELAS international collaboration.

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