Statistical Properties of Exoplanets

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Annu. Rev. Astron. Astrophys. 2007. 45:397–439

First published online as a Review in Advance on May 21, 2007.

The *Annual Review of Astronomy and Astrophysics* is online at astro.annualreviews.org

This article's doi:
10.1146/annurev.astro.45.051806.110529

0066-4146/07/0922-0397$20.00

Key Words

extrasolar planets, planet formation, radial velocity, stellar abundances

Abstract

Since the detection a decade ago of the planetary companion of 51 Peg, more than 200 extrasolar planets have been unveiled, mostly by radial-velocity measurements but also in a few cases by photometric transit observations or in microlensing experiments. They present a wide variety of characteristics such as large masses with small orbital separations, high eccentricities, period resonances in multiplanet systems, etc. Meaningful features of the statistical distributions of orbital parameters for giant planets or of parent stellar properties have emerged. We discuss them in the context of the constraints they provide for planet-formation models, and in comparison to Neptune-mass planets in short-period orbits recently detected by radial-velocity surveys. Finally, the role of radial-velocity follow-up measurements of transit candidates is emphasized. Planetary physical parameters are determined, bringing important constraints for inner planet structure models.

1. INTRODUCTION

The discovery of extrasolar planets orbiting solar-type stars is one of the major scientific breakthroughs in astronomy of the past decade. Since the first discovery by Mayor & Queloz (1995) of a planet orbiting the solar analog 51 Peg, followed soon thereafter by the detection of planets around 47 UMa (Butler & Marcy 1996) and 70 Vir (Marcy & Butler 1996), the search for extrasolar planets has evolved into a mature field in astrophysics. As of the beginning of 2007, more than 200 planetary companions have been found orbiting stars of spectral types from F to M, on orbits with periods from 1.2 days to 14 years, many of which are quite eccentric (for recent examples see Mayor et al. 2004, Vogt et al. 2005, Johnson et al. 2006, Lovis et al. 2006). The very large majority of these objects have been found with the so-called radial-velocity technique (see the sidebar, Radial-Velocity Technique). Fourteen additional candidates—some with very short periods—have also been unveiled by the photometric signature of the planet passing in front of the disk of its parent star (transits) and then confirmed by follow-up radial-velocity measurements. This flurry of discoveries is illustrated in **Figure 1** showing the temporal development of the detections, emphasizing the improvement of the precision in terms of planetary mass, and reaching now the Neptune-mass domain with radial velocities (see the sidebar, Relative Masses of Planets in the Solar System). In the diagram, we have also indicated the few detections by microlensing, a promising technique with the potential of detecting bodies of sub-Earth mass on long-period orbits (Beaulieu et al. 2006) that is very complementary to radial velocities. Even more powerful in terms of very low mass detection, pulsar timing has also revealed a few candidates (e.g., Wolszczan & Frail 1992); they are, however, not considered in this review of solar-type stars.

RADIAL-VELOCITY TECHNIQUE

The planet is unveiled by the induced change of the radial velocity of the star along its orbit around the center of mass of the star-planet system. The closer or more massive the planet, the larger the amplitude of the variation of the stellar velocity, and the easier to detect the planet. As only the radial velocity (along the line of sight) of the star is measured, we only have access to a minimum mass of the companion.

RELATIVE MASSES FOR PLANETS IN THE SOLAR SYSTEMS

Jupiter	Saturn	Neptune	Earth	Units
1.0	0.3	0.054	0.0031	[M_{Jup}]
318.4	95.23	17.3	1.0	[$M_{\oplus}$]

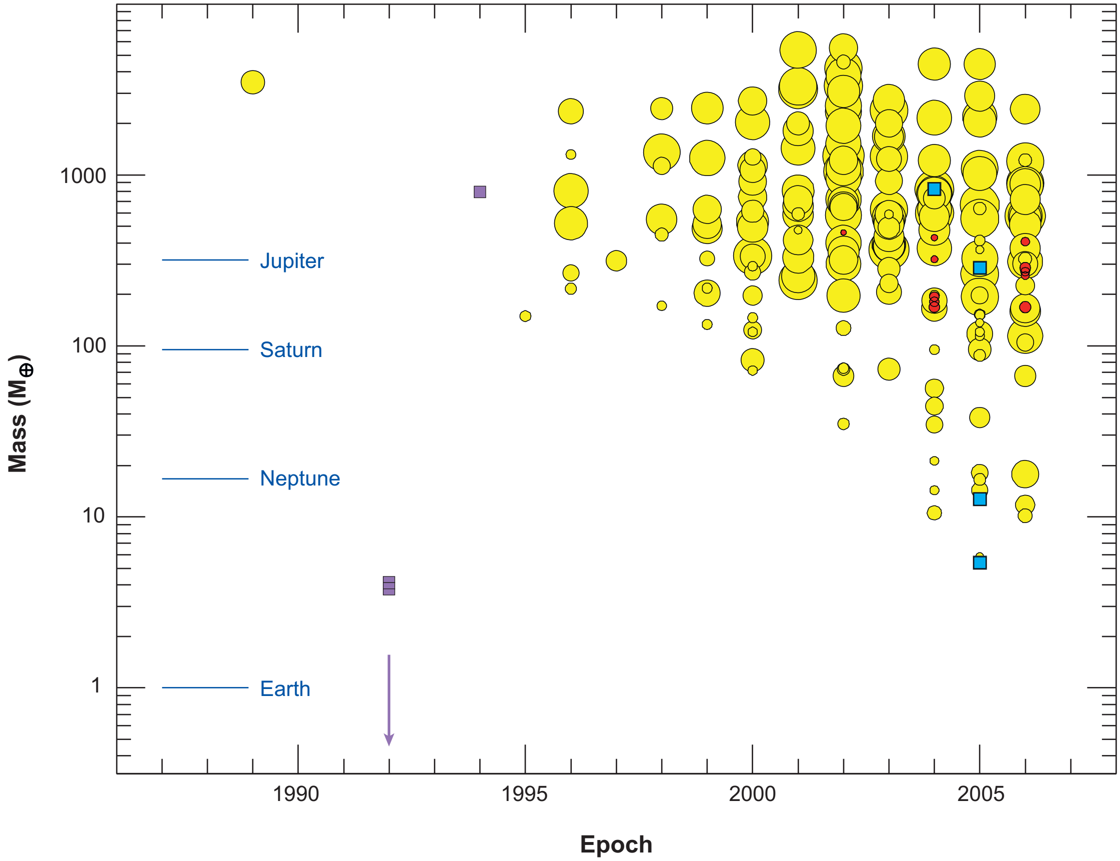


Figure 1

Masses of the known extrasolar planets in Earth masses as a function of the year of the discovery. Yellow and red circles denote planets discovered using the radial-velocity and transit techniques, respectively. The masses of the planets discovered using the radial-velocity technique are minimum masses. The size of the circles is proportional to the orbital period of the planet. Blue and purple squares represent the position of the planets discovered by microlensing and pulsar-timing surveys. The purple arrow indicates the time position of a very low-mass planet discovered by the pulsar-timing technique. The masses of Jupiter, Saturn, Neptune, and the Earth are marked for comparison. The temporal evolution of the lightest planet detection points toward a future detection of an Earth-mass planet.

The mechanisms involved in the formation of extrasolar planets remain mostly uncertain. The giant planets could have formed in circumstellar disks by accretion of solids, building up a 10 to 15 $M_\oplus$ core followed by rapid agglomeration of gas (e.g., Pollack et al. 1996; revisited by Alibert, Mordasini & Benz 2004), or by direct gravitational instability of the gas (e.g., Boss 1997, Mayer et al. 2002). The planets could then either have migrated toward the star by disk-planet interactions (e.g., Lin, Bodenheimer & Richardson 1996; Trilling et al. 1998) or have formed in-situ (Bodenheimer, Hubickyj

& Lissauer 2000). The planets potentially formed through gravitational instability are expected to be massive gaseous giants, whereas the core accretion process may end when the disk of gas dissolves but before the core has grown big enough to accrete gas in a runaway manner. The planet then remains of small mass (below 10–15 $M_{\oplus}$) and is mainly composed of solid elements with a plus-or-minus large proportion of ice/water depending on where in the system the formation has started (Alibert et al. 2006). In the very inner region of the system, Neptune-mass planets may also result from the evaporation of the gaseous atmosphere of giant planets that have migrated close to the central star (Lecavelier des Etangs et al. 2004; Baraffe et al. 2004, 2005), leaving only their rocky cores or forming ocean planets when a large fraction of ice melts because of the high temperature. A wide range of potential planet masses, sizes, and compositions results from this flurry of formation possibilities.

The regularly increasing number of known extrasolar planets brings some confidence to observed features in statistical distributions of the planet and primary star properties. These features are thought to keep fossil traces of the processes of formation or evolution of these systems and help to constrain the planet-formation models. The most remarkable feature of the sample of known planets is undoubtedly the variety of orbital characteristics, largely unexpected from the observation of our own Solar System, that challenge our standard paradigm of planetary formation. We have learned first that gas giant planets are common and second that the planetary formation process may produce a surprising variety of configurations: masses considerably larger than Jupiter, planets moving on highly eccentric orbits, planets orbiting closer than 10 stellar radii (see Hot Jupiters, sidebar below), planets in resonant multiplanet systems, and planets orbiting components of stellar binaries. Understanding the physical reasons for such wide variations in outcome remains a central issue in planet-formation theory.

Because of the nature of the radial-velocity method, only the orbital parameters and a lower limit on the planet mass are known from spectroscopic measurements alone. Much tighter constraints for planet models are obtained by the observations of a photometric transit of the planet in front of its parent star. Combined with radial-velocity measurements, such observations yield the exact mass, radius, and mean density of the planet, proving its gaseous (or solid) nature and providing priceless constraints for the planet's internal structure. For a long time, only one such case was known, HD 209458 b (Charbonneau et al. 2000, Henry et al. 2000, Mazeh et al. 2000). Now, 14 transiting planets are known, 4 announced only very recently (O'Donovan et al. 2006, Bakos et al. 2007, Collier Cameron et al. 2007). They come either from

HOT JUPITERS

Jupiter-type planets orbiting close to their parent stars, typically within 0.1 AU (i.e., $P \simeq 10$ days for a planet around a solar-type star). The name comes from the high equilibrium temperature of these planets, reaching values close to 1500 K for a separation of 0.05 AU from a solar-type star.

spectroscopically detected candidates found to transit in front of their stars or from photometric small-depth transits confirmed to be planets by radial-velocity follow up. These transiting objects allow us to draw an observed mass-radius relation in the planetary domain, providing a powerful tool to check the proposed planetary structure and atmosphere models.

Answers to the questions raised by the new discoveries will undoubtedly benefit from constraints provided by the statistical distributions of planetary orbital parameters. In the case of transit events, further planetary physical properties like radius and mean densities are then available to constrain models of the internal structure of the planets. Primary star properties are also of great help to understanding the environmental conditions favorable to planet formation. Stars with giant planets have peculiar chemical composition; they are on average more metal-rich than stars of the Solar Neighborhood. A hint of a possible primary mass effect comes from the enlargement of the parameter space to higher and lower star masses, and from very light planet discoveries.

Most of the planets detected through Doppler measurements are giant gaseous planets similar in nature to Jupiter; typical masses are of a few hundreds of Earth masses. The past three years have gone a new step forward with the detections of light (10–20 $M_{\oplus}$), potentially rocky planets by different teams (Butler et al. 2004, McArthur et al. 2004, Santos et al. 2004a, Bonfils et al. 2005a, Rivera et al. 2005, Vogt et al. 2005, Lovis et al. 2006, Udry et al. 2006, Bonfils et al. 2007, Melo et al. 2007). These detections were made possible, first, thanks to the development of a new generation of stable and more precise instruments for radial-velocity measurements and, second, by the application of a careful observing strategy to reduce as much as possible the effect of stellar oscillations hiding the tiny planet's signal. Thus, stars suitable for very high-precision radial-velocity measurements are preferably slow rotators, are nonevolved, and have low activity. Then, in order to average out stellar oscillations, the observations are designed to last at least 15 to 30 min on target (i.e., longer than typical acoustic mode timescales). The best example illustrating the efficiency of this approach is the discovery of the system around HD 69830, composed of three Neptune-mass planets (**Figure 2**; Lovis et al. 2006). The number of light solid planets, although still small, already allows us to start a first comparison of their characteristics with the properties of their giant gaseous counterparts.

In this review, we present a census of the main statistical results obtained over the past decade in the domain, focusing mainly on the more numerous candidates detected by radial velocities. We principally discuss their general orbital characteristics, the useful features of multiplanet systems, and the knowledge gained from primary star properties. Conclusions in terms of future perspectives in the field, especially toward the detection of Earth-like planets, are drawn.

Observational data used for this discussion can be retrieved from the comprehensive *Extrasolar Planets Encyclopedia* (**http://www.exoplanet.eu**) maintained by J. Schneider, from the Geneva planet-search Web pages (**http://www.exoplanets.eu** or **http://www.exoplanets.ch**), or from the Web site of the California & Carnegie planet-search team (**http://www.exoplanets.org**). General statistical results of exoplanet characteristics are similarly described in recent reviews by Marcy et al. (2005),

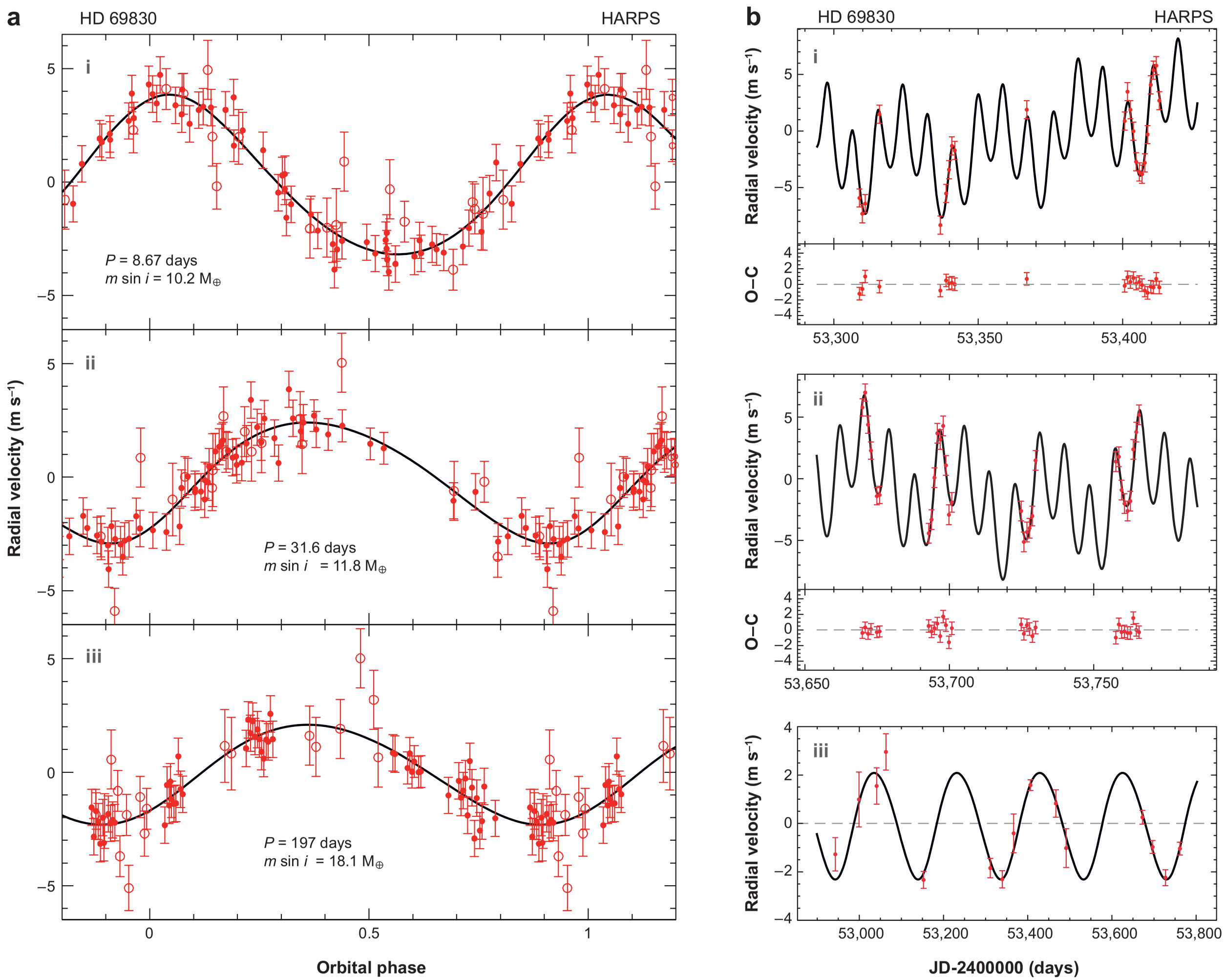


Figure 2

HARPS radial velocities of the star HD 69830 hosting a system of three Neptune-mass planets. The best three-Keplerian model of the system is superimposed to the data, in a phase-folded manner (*a*) or for given intervals of time (*b*). Run-averaged velocities after removal of the effect of the two shorter-period planets are shown in (*biii*). The measured dispersion around the solution then becomes of the order of 20–30 cm^{-1}. (From Lovis et al. 2006.)

Santos, Benz & Mayor (2005), or Udry, Fischer & Queloz (2007). Finally, the different methods for planet detection and the expectations in the field for the next decades are carefully reviewed by Perryman et al. (2005).

2. CONSTRAINTS FROM ORBITAL PROPERTIES

During the past decade, our understanding of planetary formation had to integrate several new peculiar characteristics. With the number of detected planets regularly increasing, we must continuously reexamine the statistical properties of the derived orbital elements and stellar-host characteristics, and search for constraints for the different planet formation and evolution scenarios. Some confidence to observed trends is brought by the regularly increasing number of candidate detections. The most stunning feature of the sample is the variety of orbital characteristics. This variety challenges the conventional views of planetary formation. The goal now is to interpret the observed orbital distributions in terms of constraints for the planet-formation models.

Meaningful statistical properties of giant planets should be derived from surveys that are themselves statistically well defined (e.g., volume-limited) and with well-understood built-in biases and detection thresholds in the various planet, primary-star, and orbital parameters. There are several radial-velocity programs that meet these requirements, including the volume-limited CORALIE planet-search program (1650 FGK stars; Udry et al. 2000), with its HARPS expansion of 1200 stars (Mayor et al. 2003), or the magnitude-limited FGKM Lick+Keck+AAT survey (1330 FGKM stars; Marcy et al. 2005). In the diagrams of this review, we often display all known planet candidates and note that the discussed properties agree with those presented from single well-defined programs as well.

Even if well designed, we have to keep in mind that radial-velocity surveys are not free of built-in biases inherent to the method. Pulsating stars with periodic motions of the photosphere inducing a variation of the observed radial velocities are not adequate for planet-search programs. Young, fast-rotating and/or active stars are often left out as well, because of the extra radial-velocity jitter owing to line asymmetries induced by spots on the stellar surface (Saar & Donahue 1997, Santos et al. 2000, Paulson et al. 2002, Wright 2005). Early-type stars are not easy targets either because of the smaller number of lines and of their typical high rotation rate that make high-precision radial-velocity measurements difficult. Finally, spectroscopic and close visual binaries (within 2 to 6 arcsec depending on the programs) are also discarded from the samples because of the complexity resulting from the mixing of the two stellar spectra (Section 2.5). Several programs are aimed at improving this bias in sample definition. Galland et al. (2005a,b) are conducting a very promising survey on A–F dwarf primaries in both hemispheres, probing intermediate-mass primaries in a complementary way with programs targeting giant stars of similar masses (Sato et al. 2003, 2007; Setiawan et al. 2005; Hatzes et al. 2005). In the Hyades, the long-term effort by Cochran, Hatzes & Paulson (2002), Paulson, Cochran & Hatzes (2004a), and Paulson et al. (2004b) illustrates the difficulty of radial-velocity planet search among active stars. Ongoing radial-velocity surveys in multiple-star systems have not

PERIOD-SEPARATION CORRESPONDENCE

Kepler's third law tells us that $(M_* + M_{\rm pl})P^2 = a^3$, with the period in years and the separation in AUs (1 AU corresponds to the Earth-Sun separation or $1.496 \cdot 10^{13}$ cm). For a solar-mass star, we then have $P = 10$ days at 0.09 AU or $P = 1$ year at 1 AU.

produced reliable results yet (Udry et al. 2004, Konacki 2005a, Eggenberger et al. 2007).

In addition to the limitations inherent to the detection methods, we also meet the difficulty of correctly modeling the planetary system when the orbital parameters are extreme or when the system hosts more than a single planetary companion. In both cases, a good phase coverage of the different temporal variations is very helpful if not mandatory. The modeling of an n-planet system involves $5n + 1$ free parameters, leaving room for various equal-quality potential solutions. It is then very important to characterize these solutions with the help of algorithms that allow probing the parameter space in a global manner. Genetic algorithm, Markov chain, or neuronal network approaches are very useful in this context. Predictions of orbital behaviors may then be checked with further observations. In case of multiplanet systems (Section 3), the model must also be adapted to take gravitational planet-planet interaction into account.

2.1. Occurrence Rate of Giant Planets

The most direct statistical property of a planet-search program is the fraction of detected planets among the surveyed stars. For a given precision and duration of the observations, the minimum rate is obtained by counting the fraction of stars hosting planets in the corresponding period-mass slice of parameter space (see the sidebar, Period-Separation Correspondence). In the nonbinary part of the CORALIE planet-search sample, 0.8% of stars have giant planets ($m_2 \sin i \geq 0.2$ $M_{\rm Jup}$) with separations less than 0.1 AU (hot Jupiters), and $63/1120 = 5.6\%$ of stars have giant planets at separations out to 4 AU. For planets more massive than 0.5 $M_{\rm Jup}$, Marcy et al. (2005) find in the Lick+Keck+AAT sample that 1.2% of the stars host hot Jupiters and 6.6% of stars have planets within 5 AU. Within error bars, and including a correction to account for the smaller separation range and the different planet-mass interval considered with CORALIE, these two large samples are in good agreement.

The planet occurrence frequency is better determined as a function of planet mass and orbital period using Monte Carlo simulations to estimate detection incompleteness. This has been done only in a few cases. For the ELODIE program (magnitude-limited sample of stars cleaned from known binaries; Perrier et al. 2003), although dominated by small number statistics errors, Naef et al. (2005) estimate for planets more massive than 0.5 $M_{\rm Jup}$ a corrected fraction of $0.7 \pm 0.5\%$ for hot Jupiters with $P \leq 5$ days, and of $7.3 \pm 1.5\%$ for planets with periods smaller than

3900 days (∼4.8 AU). A similar analysis has been carried out by Cumming, Marcy & Butler (1999) for the Lick survey and by Endl et al. (2002) for the planet-search program with the ESO coudé-echelle spectrometer. In the overlapping parameter space, all of these analyses show good agreements. With the continuously increasing timespan of the surveys and the improvement in our ability to detect smaller-mass planets, we expect the fraction of stars hosting planets to increase substantially from these estimated minimum values.

2.2. Distribution of Planetary Masses

Companion minimum mass and separation from the central star are the two properties of the system directly obtained from radial-velocity measurements. The known planetary mass distribution, an important constraint for formation models, is discussed in this section separately for giant gaseous planets and for the emerging population of small-mass solid planets.

2.2.1. Giant gaseous planets. It was already clear after the detection of a handful of extrasolar planets that these objects could not be considered the low-mass tail of stellar companions in binary systems (with low $m_2 \sin i$ because of nearly face-on orbital inclinations). The strong bimodal aspect of the secondary-mass distribution to solar-type primaries has generally been considered the most obvious evidence of different formation mechanisms for stellar binaries and planetary systems (e.g., Udry et al. 2002). If most of the gaseous giant planets detected have masses less than 5 $M_{\rm Jup}$, the distribution presents a long tail toward masses larger than 10 $M_{\rm Jup}$ (**Figure 3**; Jorissen, Mayor & Udry 2001; Zucker & Mazeh 2001; Tabachnik & Tremaine 2002). No real clear limit exists as the distribution goes continuously into the brown-dwarf regime but with a decreasing number of candidates. The interval between the two populations (planets and stellar binaries), the "brown-dwarf desert," corresponding to masses between ∼15 $M_{\rm Jup}$ and ∼60 $M_{\rm Jup}$, contains only a few objects, at least for orbital periods shorter than a decade (e.g., Halbwachs et al. 2000). There is, however, a probable overlap of the planet and binary distributions in the 10–20 $M_{\rm Jup}$ domain. At this point, it is not easy to differentiate low-mass brown dwarfs from massive planets (see the sidebar, Brown Dwarfs versus Planets) just from their $m_2 \sin i$ measurements without additional information on the formation and evolution of these systems. Even *Hipparcos* astrometry has been shown not to reach a sufficient precision to unambiguously probe planetary companions (Pourbaix 2001, Pourbaix & Arenou 2001). However, the situation is expected to become a bit clearer in determining the true masses for most of these objects thanks to high-angular-resolution astrometric facilities that will become available in the upcoming years on the ground (e.g., PRIMA on the VLTI) as well as in space (*Space Interferometry Mission*, i.e., SIM; or *Gaia*).

Toward the low-mass planets, a clear rise of the distribution is observed (**Figure 3*a***). Marcy et al. (2005) proposed a power-law-type function, $dN / dM \propto M^{-1.05}$, to describe the result from their FGKM sample. This fit is not affected by the unknown $\sin i$ distribution, which simply scales in the vertical direction

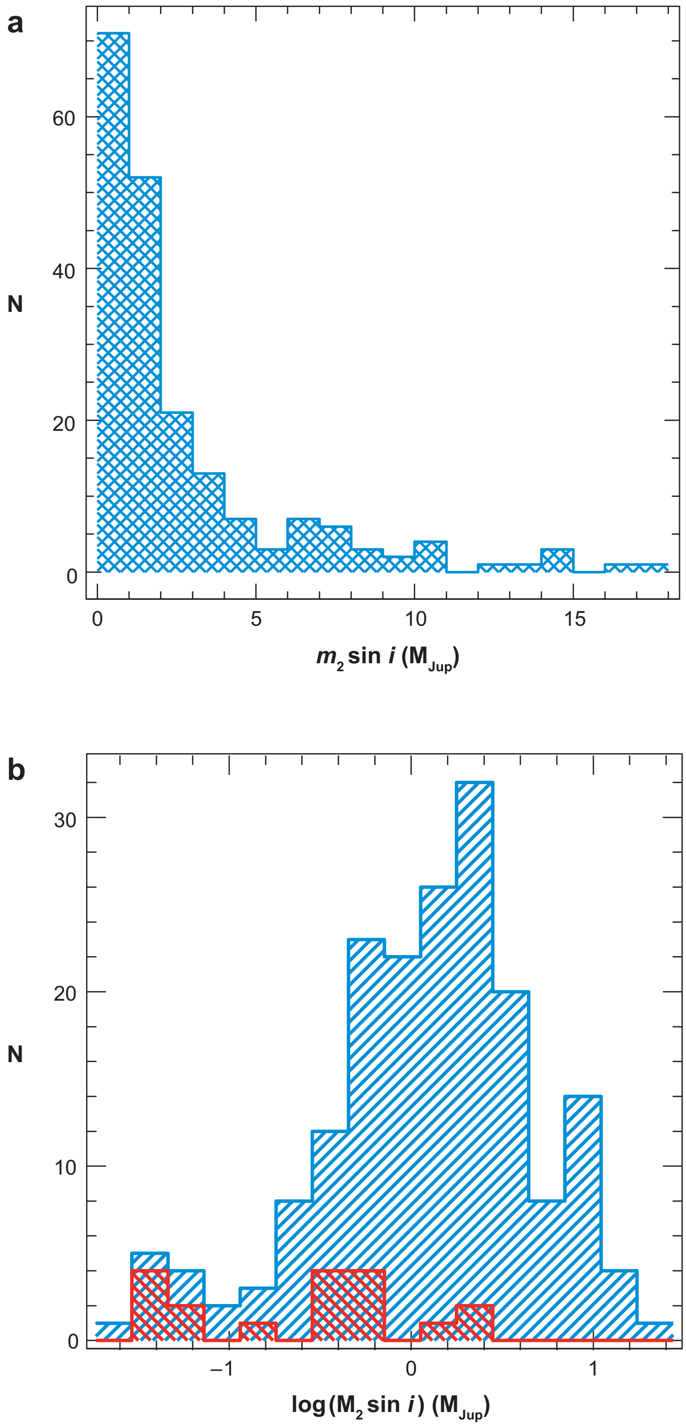


Figure 3

Planetary mass distribution in linear (*a*) and log (*b*) scales, illustrating the steep rise of the distribution toward the lowest masses and the still strong observational bias below the mass of Saturn. The double-hatched histogram in panel (*b*) indicates the masses of planets detected with HARPS, one of the new generation instruments capable of very high radial-velocity precision (Pepe et al. 2005).

BROWN DWARFS VERSUS PLANETS

Brown dwarfs are objects with masses below the H-burning limit ($\sim$75 M_{Jup}), formed as stars by fragmentation of a protostellar cloud. Planets are supposed to be built up from protostellar disk material. In the $\sim$10–$\sim$20 M_{Jup} interval, the two populations overlap, making it difficult to accurately name the companions found in this mass range.

(Jorissen, Mayor & Udry 2001). Below the mass of Saturn, the distribution is strongly affected by the detection bias inherent to radial-velocity measurements (**Figure 3*b***). We are nevertheless observing the onset of a new population of very light planets described in the next section.

2.2.2. A new population of solid planets. The low-mass edge of the planet mass distribution is poorly defined because of observational incompleteness (**Figure 3*b***). However, although the lowest-mass planets are difficult to detect, in the past three years 12 planets with masses in the Uranus-Neptune range ($\leq$20 $M_\oplus$) have been detected (Butler et al. 2004, McArthur et al. 2004, Santos et al. 2004a, Bonfils et al. 2005a, Rivera et al. 2005, Vogt et al. 2005, Lovis et al. 2006, Udry et al. 2006, Bonfils et al. 2007, Melo et al. 2007). [The smallest value of planet minimum mass measured so far (beginning of 2007) by radial velocities is $\sim$6 M_{Earth} for the planet orbiting the M-dwarf primary Gl 876 (Rivera et al. 2005), and the smallest detected amplitude (2.2 ms^{-1}) is for the longest-period planet in the 3-Neptune system (**Figure 2**) discovered around HD 69830 (Lovis et al. 2006).] 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 & 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 et al. 2004; 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 object 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 $M_\oplus$, Beaulieu et al. 2006), showing that smaller-mass planets can be found over a large range of separations where they should be common (Gould et al. 2006). This is in complete agreement with the latest Monte Carlo simulations of accretion-based planet formation models predicting large numbers of solid planets (Ida & Lin 2004a, 2005; Alibert, Mordasini & Benz 2004; Benz et al. 2006). In this line of thought, we already can note in **Figure 3*a*** that the detected Neptune-mass planets build a distribution of their own with a gap starting to appear between them and the more common Jupiter-mass planets. Although this result is still strongly observationally biased, it will be interesting to see if the properties of the two populations show further differences, especially when the available statistics increase.

2.3. Orbital Period Distribution of Exoplanets

The distribution of periods of giant exoplanets is basically made of two main features (**Figure 4**): a peak around 3 days plus an increasing distribution with period (Cumming, Marcy & Butler 1999, Udry, Mayor & Santos 2003, Marcy et al. 2005). The hot Jupiters were completely unexpected before the first exoplanet discoveries. The standard model (e.g., Mizuno 1980, Pollack et al. 1996, Rice & Armitage 2003) suggests that giant planets form first from ice grains in the outer region of the system where the temperature of the stellar nebula is cool enough. Such grain growth provides the supposed requisite solid core around which gas could rapidly accrete (Safronov 1969) over the lifetime of the protoplanetary disk ($\sim 10^7$ year, e.g., Haisch, Lada & Lada 2001). During this process, they are also supposed to undergo a migration process moving them from their birth place close to the central star (see, e.g., Lin, Bodenheimer & Richardson 1996; Ward 1997; Papaloizou & Terquem 2006), where they have to stop before falling onto the star. Several stopping mechanisms have been proposed, invoking, e.g., a magnetospheric central cavity of the accretion disk, tidal interactions with the host stars, Roche-lobe overflow by the young inflated giant planet, or photoevaporation. The question is, however, still debated. Alternative points of view invoke in situ formation (Bodenheimer, Hubickyj & Lissauer 2000), possibly triggered through disk instabilities (Boss 1997, Durisen et al. 2007). Note however that, even in such cases, subsequent disk-planet interactions leading to

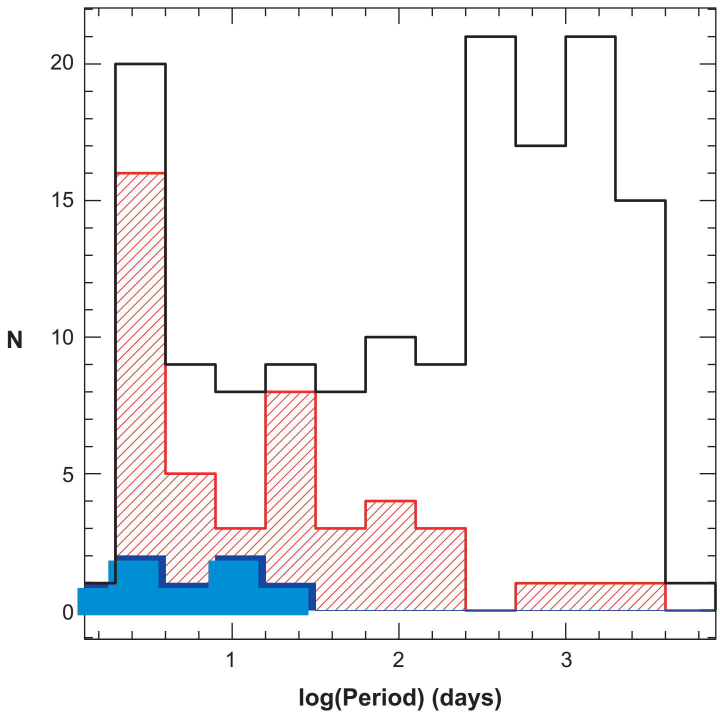


Figure 4
Period distribution of known gaseous giant planets detected by radial-velocity measurements and orbiting dwarf primary stars (open histogram). The red hatched part of the histogram represents light planets with $m_2 \sin i \leq 0.75\ M_{Jup}$ that probably have migrated toward the center of the system. For comparison, the period distribution of known Neptune-mass planets (with short periods and masses $\leq 21\ M_{\oplus}$) is given by the blue filled histogram, showing a flatter distribution with periods up to 30 days. (Note, however, that there is still very high observational incompleteness for these low-mass planets).

migration is expected to take place as soon as the planet has formed. The observed pile up of planets with periods around 3 days is believed to be the result of migration and final stopping mechanism (see, e.g., Udry, Mayor & Santos 2003, and references therein, for a more detailed discussion). The exact distance range related to the stopping mechanism is not well defined. A small tail of the distribution points toward the small separations. In particular, three of the transiting planets in the OGLE survey (Udalski et al. 2002a,b) have periods smaller than 2 days (very hot Jupiters). Such short periods, although easy to detect, are not found in the radial-velocity surveys, suggesting that those objects are about 10 times less numerous than hot Jupiters (Gaudi, Seager & Mallen-Ornelas 2005; see also Section 5).

Another interesting feature of the period distribution is the rise of the number of planets with increasing distance from the parent star, up to a separation corresponding to the duration limit of most of the older surveys (4–5 AU). This is not an observational bias, as equivalent mass candidates are more easily detected at shorter periods with the radial-velocity technique. The position of the maximum of the distribution is unknown. However, a conservative flat extrapolation of the present distribution out to larger separations would approximately double the occurrence rate of planets (Marcy et al. 2005). This extrapolation hints that a large population of yet undetected Jupiter-mass planets may exist between 3–20 AU. This is of prime importance for the direct-imaging projects under development on large telescopes such as SPHERE, the VLT Planet Finder, or the Gemini Planet Imager (Beuzit et al. 2007), and space-based imaging missions such as NASA's *James Webb Space Telescope* (JWST) and *Terrestrial Planet Finder*, or ESA's *Darwin*.

2.3.1. Period distribution of Neptune-mass planets. Although the number of known Neptune-mass planets is small, it is interesting to see how their orbital parameters compare with properties of giant extrasolar planets. Because of the tiny radial-velocity amplitude they induce on the primary stars, limiting detections to short orbital periods, a meaningful comparison can only be done for giant planets with periods smaller than ~20 days. As mentioned above, the distribution of short-period giant planets peaks where periods are around 3 days. On the contrary, despite the mentioned detectability bias, the period distribution of Neptune-mass planets is rather flat up to 30 days (**Figure 4**). We even have a candidate with a six-month period (Lovis et al. 2006). This hints at another difference in the properties of Neptune- and Jupiter-mass planets at short periods.

2.4. The Period-Mass Diagram

The study of the orbital period distribution has shown the importance of considering migration processes to explain the observed configuration of planetary systems. When coupling period and mass, further striking features appear in the distribution. **Figure 5** displays the mass-period diagram for the known exoplanets orbiting stars on the Main Sequence (dwarfs). The first noticeable characteristic of the distribution is the lack of massive planets on short-period orbits (Pätzold & Rauer 2002, Udry et al. 2002, Zucker & Mazeh 2002). Even more striking, when we ignore the multiple-star

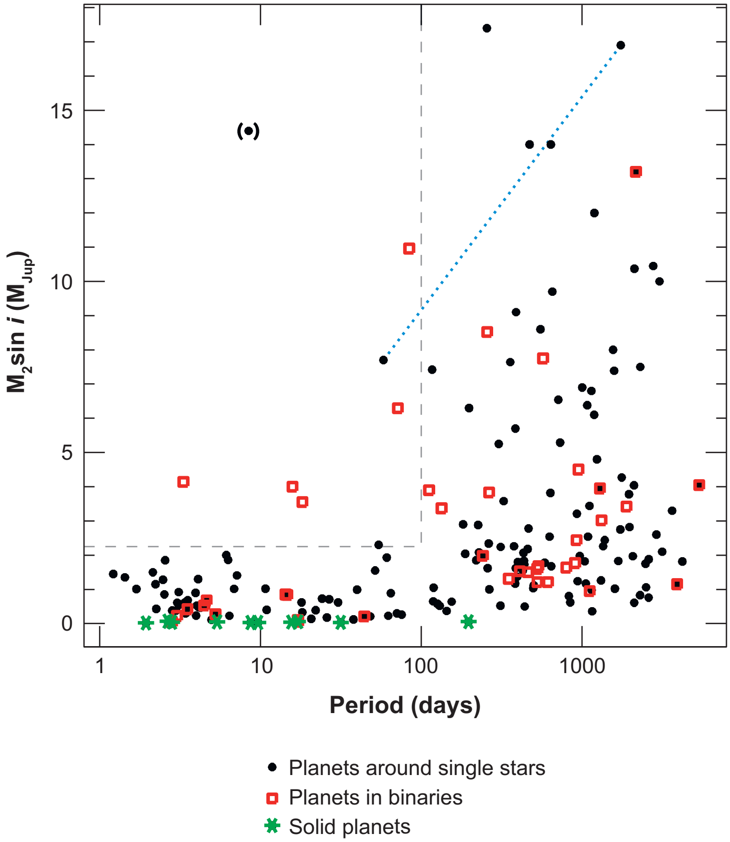


Figure 5

Period-mass distribution of known extrasolar planets orbiting dwarf stars. Gray dashed lines are limits at 2.25 M_{Jup} and 100 days. The blue dotted line connects the two massive components orbiting HD 168443, and the parentheses indicate the position of the probable brown dwarf HD 162020.

systems, we completely miss candidates with masses larger than ~2 M_{Jup} and periods smaller than ~100 days (see Section 2.5). [Beyond this, the only candidate left is HD 168443 b, which is possibly a member of a multi-brown-dwarf system (Marcy et al. 2001, Udry et al. 2002).] This is not an observational bias as these candidates are the easiest ones to detect. Migration scenarios may naturally result in a paucity of close-in massive planets. Type II migration, when a planet is massive enough (>0.5–1.0 M_{Jup}) to clear a gap in the disk, has been shown to be less effective for massive planets (Trilling et al. 1998; Nelson et al. 2000; Trilling, Lunine & Benz 2002); i.e., massive planets are stranded at wider separations than low-mass planets. Moreover, when a migrating planet reaches small separations from the star, some process related to planet-star interactions could promote mass transfer from the planet to the star, decreasing the mass of the migrating planet (e.g., Trilling et al. 1998), or cause massive planets to fall into the central star (Pätzold & Rauer 2002).

Another interesting feature of the distribution is the rise in the maximum planet mass with planet-star separation (Udry, Mayor & Santos 2003). Massive planets are easily detected at small separations, yet they preferentially reside in more distant orbits. This can be understood in the context of the migration scenario as well. More massive planets are expected to form further out in the protoplanetary disk (out to a maximum distance for planet formation probably set by the size of the protoplanetary disk, Pollack et al. 1996), where raw materials for accretion are available along a longer orbital path, thus providing a larger feeding zone. Then, migration may be more difficult to initiate as a larger portion of the disk has to be disturbed to overcome the inertia of the planet.

To explain the observed correlation, it has also been suggested that multiplanet chaotic interactions preferentially move low-mass (low-inertia) planets either inward or outward in the system, whereas massive (high-inertia) planets are harder to dislodge from their formation site (Rasio & Ford 1996, Weidenschilling & Marzari 1996, Marzari & Weidenschilling 2002, Levison et al. 2007). It is however still an open question whether the correct frequency of hot Jupiters can be reproduced this way (Ford, Havlickova & Rasio 2001; Ford, Rasio & Yu 2003).

Simulations of migrating planets in viscous disks are consistent with the observation of a decrease in the efficiency of migration with increasing planet mass (Trilling et al. 1998; Nelson et al. 2000; Trilling, Lunine & Benz 2002). Therefore, it seems reasonable to expect that a large number of massive planets may reside on long-period orbits, some still undetected because of the time duration of the present surveys. Bright planets around young primary stars, less amenable to radial-velocity searches because of the intrinsic stellar astrophysical noise, will be suitable targets for direct imaging searches (Beuzit et al. 2007). Lower mass planets exist on long-period orbits as well (e.g., Uranus and Neptune), however these planets are difficult to detect with precisions ≥ 3 ms^{-1}. The detection of very low-mass, distant planets orbiting chromospherically quiet stars will require extreme precision radial velocities with demonstrated stability over a decade or more. Microlensing should produce a better statistical view on this part of the mass-period parameter space (Gould et al. 2006).

2.5. Planets Orbiting Components of Multiple-Star Systems

Searches for extrasolar planets using the radial-velocity technique have shown that giant planets exist in certain types of multiple-star systems. Faint stellar companions to star-hosting planets are also unveiled by dedicated high-angular-resolution imaging programs. Among the ~200 extrasolar planets discovered to date by radial velocities, more than 30 are known to orbit one of the members of a double or multiple-star system (Patience et al. 2002; Eggenberger, Udry & Mayor 2004; Mugrauer et al. 2005; Raghavan et al. 2006; Desidera & Barbieri 2007). Some simulations suggest that planet formation could be inhibited in similar-mass close-enough binary systems ($\lesssim$50 AU; e.g., Nelson 2000), yet the actually observed systems with planets cover a large range of binary-projected separations: from ~20 AU for three spectroscopic binaries to more than 1000 AU for wide visual binaries. In fact, a planet candidate revealed by radial velocities in the close visual binary system HD 188533 (12 AU separation; Konacki 2005b) is now seriously questioned by new observations (Eggenberger et al. 2007), the observed signal being caused by perturbing effects of the mixing of the light coming from three different stars.

Although the sample is not large, some differences between planets in binaries and around single stars are observed. Zucker & Mazeh (2002) pointed out that the most massive short-period planets are all found in binary or multiple-star systems. A planet orbiting the component of a multiple-star system also tends to have a very low eccentricity when its orbital period is shorter than about 40 days (Eggenberger, Udry & Mayor 2004). The only known exception to this is the massive companion of HD 162020, which is probably a low-mass brown dwarf (Udry et al. 2002). These differences are compelling for planet-formation models and call for a clear separation of the subsamples of planets in binaries and planets around single stars when interpreting their properties in terms of constraints for models of planet formation and evolution.

On the contrary, no obvious correlation has yet been observed between the properties of these planets and the known orbital characteristics of the binaries (e.g., projected separations) or of the stellar component physical properties (e.g., masses). Note however, that the statistics are still poor and that the complete binary orbital parameters are generally not known.

The number of planets orbiting a component of a binary system is still low, in part because close binaries are difficult targets for radial-velocity surveys (Udry et al. 2004, Konacki 2005a, Eggenberger et al. 2007). However, even if the detection and characterization of planets in binaries are more difficult to carry out than the study of planets around single stars, it is worth doing because of the new constraints and information it may provide on planet formation and evolution. In particular, circumbinary planets offer a completely unexplored field of investigations.

Owing to the limitations of the available observational techniques, most detected objects are giant (Jupiter-like) planets; the existence of smaller mass planets in multiple-star systems is still an open question.

2.6. Planet Orbital Eccentricities

With a median eccentricity of 0.29, extrasolar planets with orbital periods longer than about 6 days have eccentricities significantly larger than those of giant planets in the Solar System. The eccentricity distribution for these exoplanets resembles that for binary stars, spanning almost the full range between 0–1. This enigmatic result is illustrated in **Figure 6**. A quick look at the diagram shows that there are no clear differences between the eccentricity distributions of planetary and stellar binary systems. How can two groups of bodies, formed by physically different processes, have basically the same distribution in this plot? How does this compare with the traditional understanding of a planet forming in a disk? Actually, for masses lower than $\sim$10–15 M_{Jup}, it has been suggested that the interaction (and migration) of a companion within a gaseous disk may damp the planet eccentricity (Goldreich & Tremaine 1980, Ward 1997). This implies that other processes may play an important role in defining the final orbital configuration.

The origin of the eccentricity of extrasolar giant planets has been proposed to arise from several different mechanisms: the interaction with the gaseous disk itself (Goldreich & Sari 2003), the gravitational interaction between multiple giant planets (Rasio & Ford 1996, Weidenschilling & Marzari 1996, Lin & Ida 1997, Chiang &

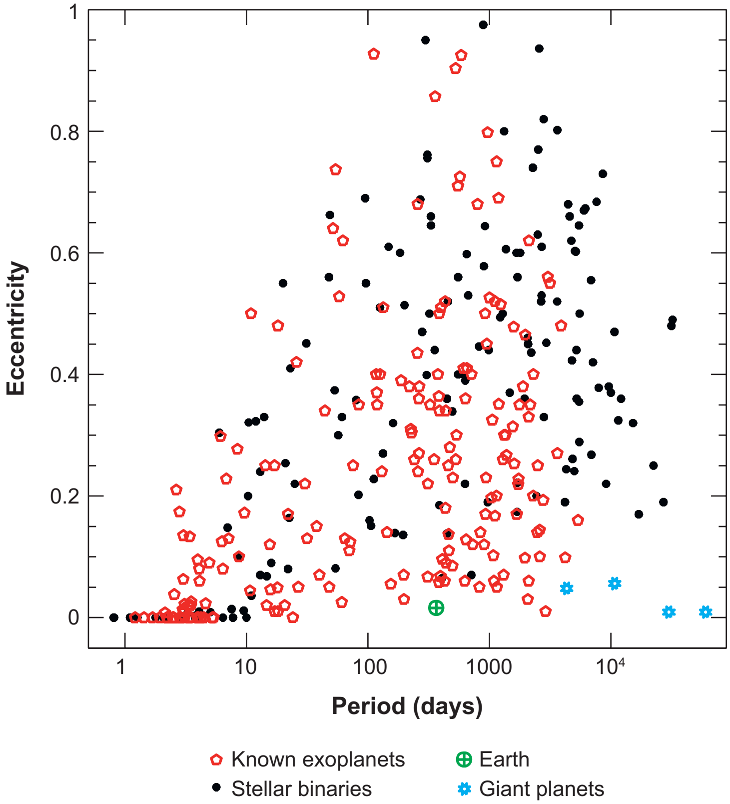


Figure 6

Period-eccentricity diagram for the sample of known exoplanets in comparison with stellar binaries. The Earth and giant planets of the Solar System are indicated as well.

Murray 2002), interactions between the giant planets and planetesimals in the early stages of the system formation (Levison, Lissauer & Duncan 1998, Murray et al. 1998), or the secular influence of an additional, passing-by (Zakamska & Tremaine 2004) or bounded companion in the system (e.g., Mazeh, Krymolowski & Rosenfeld 1997; Wu & Murray 2003).

The latter effect seems particularly interesting in some cases. The systemic velocity in several eccentric planetary orbits shows a drift, consistent with the presence of a long-period companion. The gravitational perturbation arising from the more distant companion could be responsible for the observed high orbital eccentricity. This effect has been suggested as an eccentricity pumping mechanism for the planet orbiting 16 Cyg B (Mazeh, Krymolowski & Rosenfeld 1997). However, Takeda & Rasio (2005) have shown that such a process would produce an excessive number of both very high ($e \geq 0.6$) and very low ($e \leq 0.1$) eccentricities, requiring at least one additional mechanism to reproduce the observed eccentricity distribution. Up to now, none of the proposed eccentricity-inducing mechanisms is able to reproduce by itself the observed eccentricity distribution.

A close inspection of **Figure 6** permits one, however, to find a few small differences between the eccentricities of the stellar and planetary companions. For example, for periods in the range 10 to 30 days, clearly outside the circularization period by tidal interaction with the star, there are a few systems with very low eccentricities; no stellar binaries are present in this region. The same and even more conspicuous trend is seen for longer periods, suggesting the presence of a group of planetary companions with orbital characteristics more similar to those of the giant planets in the Solar System (long period, small eccentricity; they form a small subsample of so-called Solar System analogs). For the short period systems ($6\mathrm{d} \leq P \leq 10\mathrm{d}$), we can see some planetary companions with eccentricities higher than those found for stellar companions of similar periods. These facts may be telling us that different formation and/or evolution processes took place: for example, the former group may be seen as a sign of formation (and evolution) in a disk, and the latter one as evidence of the gravitational influence of a longer period companion on the eccentricity.

Giant planets with small periastron distances are likely to undergo tidal circularization. For periods smaller than ~6 days, nearly all gaseous giant planets are in quasi-circular orbits (Halbwachs, Mayor & Udry 2005). A few border cases have been recently detected from a small number of observations in surveys biased for short-period orbits (metallicity-biased or photometric-transit searches) and have very uncertain eccentricity estimates (even compatible with zero). With more radial-velocity data spanning several orbits, the measured orbital eccentricities may decline. Alternatively, as mentioned above, an additional companion may ultimately be found in some of these systems. In multiple planet systems, a single Keplerian model can also absorb some of the longer period trends in mean velocities, artificially inflating the orbital eccentricity.

Trends of correlations can be seen as well between eccentricity and period, and between eccentricity and mass. The more massive planets (i.e., more massive than 5 M_{Jup}) exhibit systematically higher eccentricities than planets of lower masses (Marcy et al. 2005). If planets form initially in circular orbits, the high eccentricities of massive ones are puzzling because massive planets have the largest inertial resistance to perturbations driving them out of their initial circular orbits. The more massive planets are however found at wider separations (Section 2.4); eccentricity and orbital period are therefore coupled.

We also observe that orbits of Neptune-mass planets have in general small eccentricities. In particular for periods between 9–15 days (4 out of the 12 candidates), the mean eccentricity value is much smaller than that of giant planets. At periods smaller than 6 days, orbits are supposed to be tidally circularized, especially if these planets are solid (Goldreich & Soter 1966). However, among them, the largest observed eccentricities are for low-mass planets, whereas giant planets show lower values. More data and better eccentricity estimates will be needed to address this question.

3. MULTIPLANET SYSTEMS

An increasing number (21) of multiplanet systems have been detected. They represent ~11% of the 180 planet-bearing stars. The most prolific of them are 55 Cnc (McArthur et al. 2004) and μ Ara (HD 160691; Pepe et al. 2007), with four detected planets. υ And, HD 37124, HD 69830, and Gl 876 each have three planets, leaving

15 other known double-planet systems. The probability of finding a second planet is enhanced by a factor of almost two over the ∼7% probability of finding the first planet.

The fraction of known multiplanet systems is certainly a lower limit. Among the ∼100 stars in the long-running, radial-velocity program at Lick there are 4 multiplanet systems corresponding to half of the planet-hosting stars in the sample. For the somewhat younger ELODIE planet-search program in Haute-Provence, started in 1994 and enlarged in 1996, 25% of the stars with detected planets host more than one planet.

One difficulty complicating the detection of multiplanet systems is that the low-amplitude variations induced by more distant, longer period planets are easily absorbed into single-planet Keplerian models. Detection of additional planets is also easier in systems where the more distant planet produces larger velocity amplitudes. Those more massive planets are however less numerous (**Figure 3**). Another difficulty for multiplanet systems with intermediate orbital periods is that dynamical interactions between planets can make the modeling of the observations more difficult and delay the whole system characterization. Taking these considerations into account, and given the higher rate of multiplanet systems in the older long-running search programs, as well as the significant number of stars with planets that show an additional drift of their radial velocity indicative of another, still uncharacterized, companion in the system (Fischer et al. 2001), it seems likely that most stars form systems of planets rather than isolated, single planets. Future surveys exploiting new detection techniques complementary to radial velocities, as direct imaging, interferometry or astrometry, will very probably take advantage of the large fraction of multiple planet systems when building up their samples.

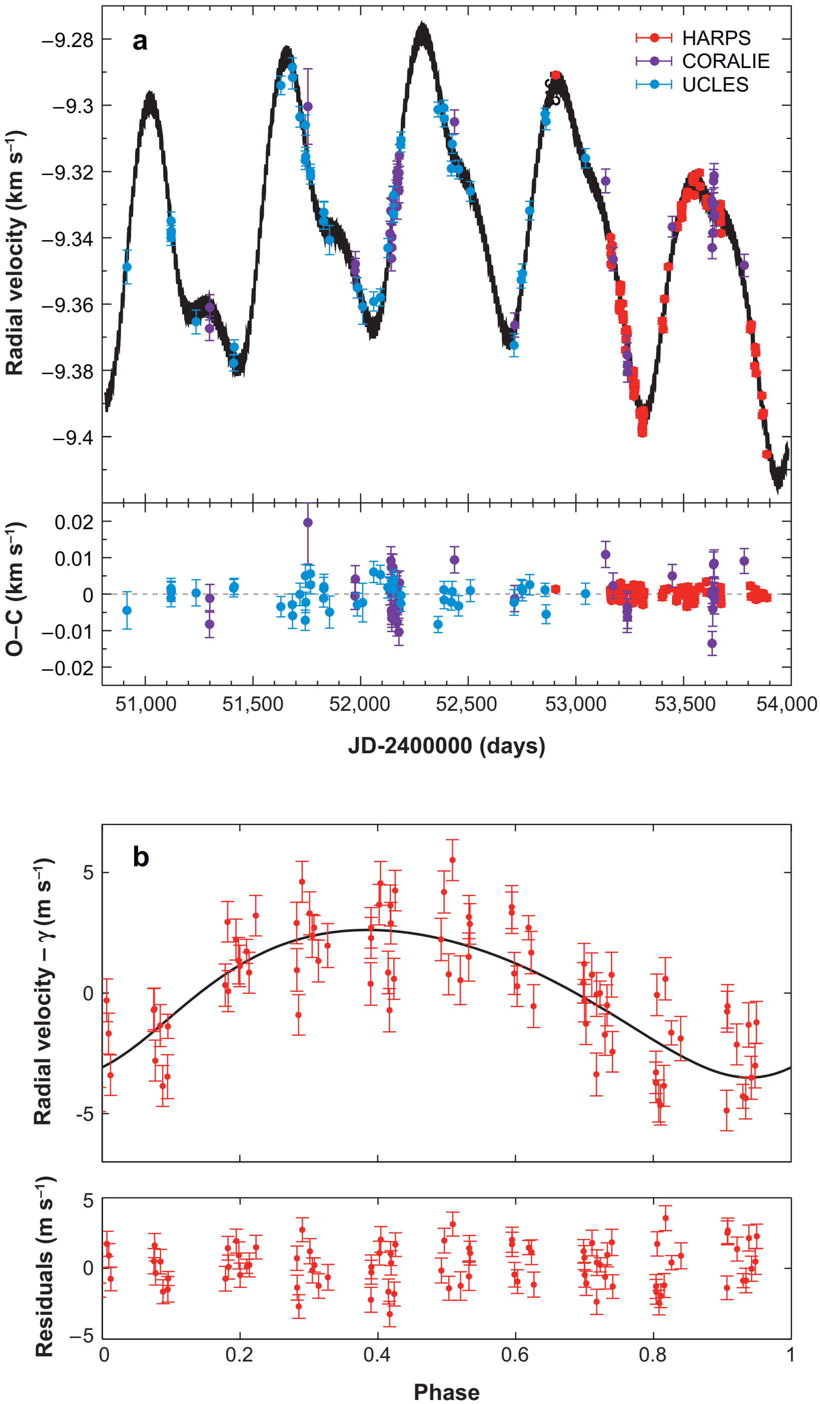
3.1. Hierarchical and Resonant Systems

The known multiplanet systems roughly appear as either hierarchical (large separation between the planets) or resonant systems. In some cases, like, for example, the four-planet system around μ Ara (**Figure 7**; Pepe et al. 2007), both configurations are present. Among the multiplanet systems, at least nine (nearly half) are in mean motion resonances: five of these are in the low order 2:1 resonance; the others are close to the 3:1 and 4:1 resonances. This suggests that if planets come close enough, they are more likely trapped into resonances. On the contrary, resonance capture seems less effective if the orbital period ratio is larger (although longer orbital periods are not as precisely determined). This is however not a definite rule as, for example, the stability study of HD 202206 (Correia et al. 2005) suggests that the system is trapped in a 5:1 resonance. For this latter case, taking into account the large minimum mass (17 $M_{\rm Jup}$) of the inner planet and following results of simulations of planet formation in circumbinary disks (Nelson 2003) that produce trapping in higher order resonances, the 5:1 resonance could indicate that the outer planet (2.4 $M_{\rm Jup}$) actually formed in a circumbinary disk.

For period ratios less than 20, we do not see any correlation between the mass ratio of the planets and the orbital period ratios. For larger period ratios, large planet-mass

Figure 7

(*a*) Radial-velocity variations of the star μ Ara produced by a cortege of four planets with masses ranging from 10.5 $M_{\oplus}$ to 3 M_{Jup} (Pepe et al. 2007). Observations were obtained with the UCLES, CORALIE, and HARPS spectrographs. (*b*) Phase-folded radial velocities of the short-period lightest planet, after removing the effect of the three longer period planets.



ratios are observed. This is likely due to the detection bias favoring massive planets on longer period orbits.

From the statistical point of view, the orbital parameters of multiplanet systems seem indistinguishable from those of single-planet systems. This is a further indication in favor of planets forming naturally in multiplanet systems.

3.2. Dynamics: Planet-Planet Interaction and Stability

The presence of two or more interacting planets in a system significantly increases our potential ability to constrain and understand the processes of planetary formation and evolution through their mutual gravitational interactions. Planet-planet interactions may be active on different timescales: interactions during the planet formation, ongoing secular or resonant interactions that can be observed on timescales of decades or less, and long-term dynamical interactions that shape the system on a timescale comparable to the star lifetime. Short-term dynamical interactions are of particular interest because of the directly observable consequences.

Among these interactions, the observed $P_i{:}P_j = 2{:}1$ resonant systems are very important because, when the planet orbital separations are not too large, planet-planet gravitational interactions become non-negligible during planet close encounters, and will noticeably influence the system evolution on a timescale of the order of a few times the long period. The radial-velocity variations of the central star will then differ substantially from velocity variations derived assuming the planets are executing independent Keplerian motions (**Figure 8**). We observe a temporal variation of the

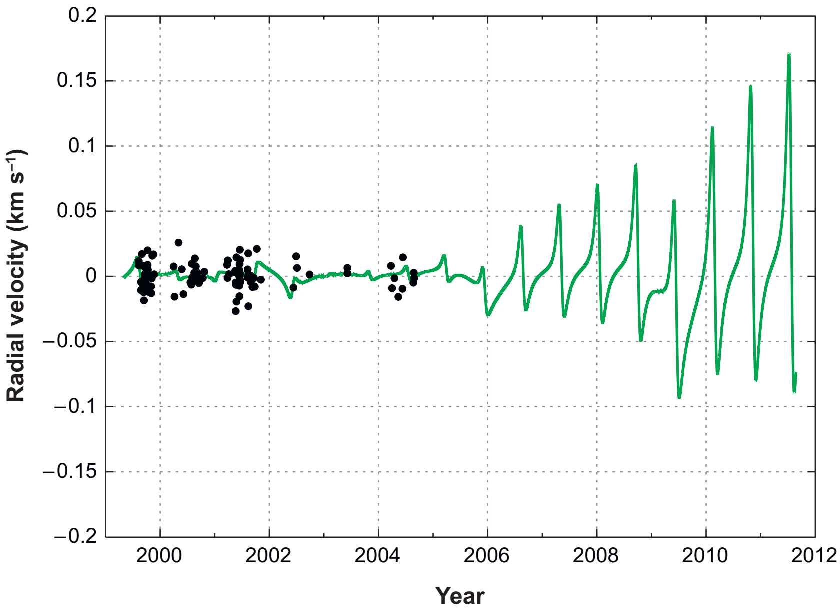


Figure 8

Temporal differences between the radial velocities predicted by the two-Keplerian model and the numerical integration of the system HD 202206 (Correia et al. 2005). Points represent the residuals of the CORALIE measurements around the Keplerian solution.

instantaneous orbital elements. In the most favorable cases, the orbital-plane inclinations, not otherwise known from the radial-velocity technique, can be determined because the amplitude of the planet-planet interaction directly scales with their true masses.

In the case of multiple planets, only approximate analytic solutions of the gravitational equations of motion exist, and one must resort to numerical integrations to model the data. Several studies have been conducted in this direction for the Gl 876 system (e.g., Laughlin et al. 2005, Rivera et al. 2005) hosting two 2:1 resonant giant planets at fairly small separations. The results of the Newtonian modeling of the Gl 876 system have validated the method, notably improving the determination of the planetary orbital elements and also unveiling the small-mass planet embedded in the very inner region of the system (Rivera et al. 2005). It is interesting to note here that the derived planet inclination ($i \simeq 50^{\circ}$; planets supposed coplanar) does not correspond to the astrometric value obtained with the *Hubble Space Telescope* (HST) for the longer period planet ($i = 84^{\circ}$; Benedict et al. 2002), suggesting a possible noncoplanarity of the different planet orbits. Further radial-velocity measurements will undoubtedly help to better characterize the system.

Another useful application of the dynamical analysis of a multiplanet system is the determination of the system structure in terms of orbit content or, in other words, the determination of the location of the resonances in the system. For example, in the HD 202206 system (Correia et al. 2005), the large mass of the inner planet provokes significant perturbations on the orbit of the outer one. The system is in a very chaotic region of parameter space, but the existence of a 5:1 mean motion resonance close to the best solution fitted to the observations provides a more realistic set of parameters that stabilizes the orbits of the two planets. A similar situation occurs for the μ Ara four-planet system (Pepe et al. 2007). The unstable minimum χ^2 solution derived from the radial-velocity measurements has to be slightly changed in order for the system to be stable, unveiling a 2:1 period resonance between planets b and d in the system.

4. PROPERTIES OF PLANET-HOST STARS

Given that planet formation is a by-product of the stellar formation process, a close look at planet-host stars is also expected to provide important clues about the formation of planetary systems. In this context, several researchers looked for correlations between the presence of planets and different stellar properties, like stellar chemical composition, mass, age, activity, and rotation. Such correlations could either provide evidence about the requisites for planet formation, or be the result of some kind of planet feedback into the star. In this section we review the main results of this research.

4.1. Metallicity of Giant-Planet Hosts

Soon after the discovery of the first exoplanets, stellar spectroscopists noticed that the stars hosting giant planets were systematically metal-rich (e.g., Gonzalez 1997, 1998; Fuhrmann, Pfeiffer & Bernkopf 1997). With the number of exoplanets growing, studies of the chemical properties of planet hosts proceeded, increasing the statistical meaning of this result (see e.g., Santos, Israelian & Mayor 2000, 2001, 2004; Gonzalez et al. 2001; Sadakane et al. 2002; Heiter & Luck 2003; Laws et al. 2003; Fischer & Valenti 2005; Santos et al. 2005; and references therein). The first detailed spectroscopic uniform studies, comparing stellar metallicities for planet hosts with those found for large comparison samples of field dwarfs (Santos, Israelian & Mayor 2001, 2004; Fischer & Valenti 2005, Bond et al. 2006), completely confirmed the validity of the planet-metallicity correlation for the observed sample of extrasolar planets (**Figure 9**).

The consistency of these results is confirmed by the use of different techniques to derive the stellar metallicities, both spectroscopic (e.g., Laws et al. 2003; Santos,

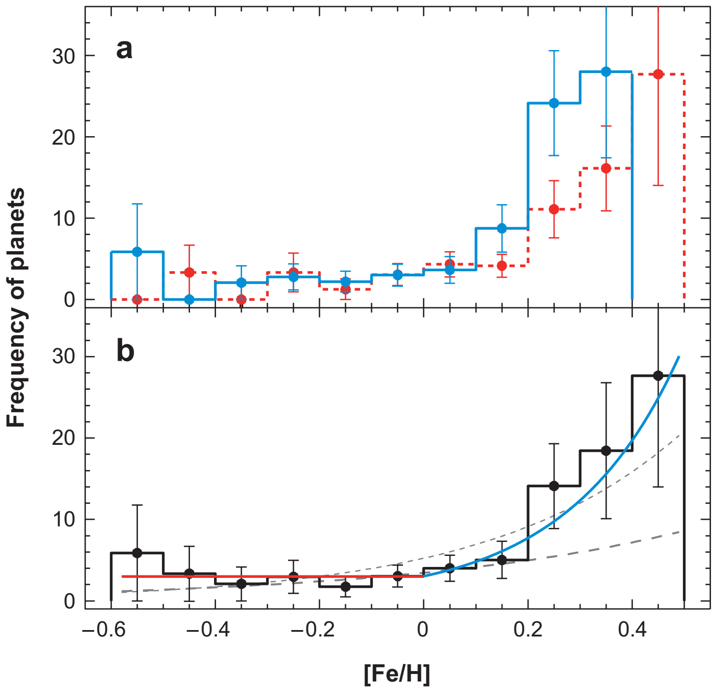


Figure 9

(*a*) Percentage of planet hosts found amid the stars in the CORALIE (*blue*) and Lick-Keck (*dashed red*) samples as a function of stellar metallicity. Data taken from Santos, Israelian & Mayor (2004) and Fischer & Valenti (2005). The lowest-metallicity bins have few planets detected, and their statistics are poor. The difference between the two distributions is probably explained by differences in the samples and in the metallicity analysis method. (*b*) Average distribution of the two samples. The blue curve represents a power-law fit to the data using only the points with [Fe/H] > 0.0. This fit provides a relation: frequency $= 3.01 \times 10^{2.04[Fe/H]}$. The red line represents the median value of the metallicities for [Fe/H] < 0.0. The gray dotted and dashed lines represent the nonweighted and weighted fits to the whole data set, respectively, done only with the data for [Fe/H] ≥ -0.5. The difficulty in fitting one single power-law to the whole range of metallicities suggests that there may be two regimes of planet formation (Santos, Israelian & Mayor 2004).

Israelian & Mayor 2004; Fischer & Valenti 2005) and photometric (e.g., Giménez 2000, Martell & Laughlin 2002, Reid 2002). It was further shown that the observed metallicity excess does not come from any observational bias. For instance, this result is obtained even if we exclude the planet hosts whose planets were discovered in the context of metallicity-biased planet-search programs (e.g., da Silva et al. 2005, Sato et al. 2005). The achieved radial-velocity precision also does not significantly depend on the metallicity of the star (e.g., Santos et al. 2003, Fischer & Valenti 2005). Curiously, some support to this may also come from the study of planetary nebulae (Balick & Frank 2002, Soker 2002).

4.1.1. The origin of the excess. The origin of this metallicity excess has been a matter of great debate. Two main hypotheses have been put forward in the literature. Some researchers suggest that the high metal content of the planet-host stars may have an external origin, resulting from the addition of metal-rich (hydrogen-poor) material into the convective envelope of the star. Such a pollution process could be induced by the planetary formation process itself (Laughlin & Adams 1997; Gonzalez 1998; Laughlin 2000; Gonzalez et al. 2001; Smith, Cunha & Lazzaro 2001; Murray & Chaboyer 2002). Evidence for the infall of planetary material has been discussed in the literature for a few planet-host stars (e.g., Cochran et al. 1997; Gonzalez 1998; Israelian et al. 2001, 2003; Laws & Gonzalez 2001; Reddy et al. 2002; Zucker et al. 2002), but this process may not be able to considerably change their overall metal content (see, e.g., Sandquist et al. 1998, 2002; Pinsonneault, DePoy & Coffee 2001; Montalban & Rebolo 2002; Santos et al. 2003).

Most current evidence (based primarily on stellar structure considerations) strongly suggest that the metallicity excess as a whole has an interstellar origin (Pinsonneault, DePoy & Coffee 2001; Sadakane et al. 2002; Santos et al. 2003; Fischer & Valenti 2005). This is further supported by the huge quantities of pollution by hydrogen-poor material needed to explain the metallicity excess observed in a few late-type, very metal-rich dwarfs known to harbor giant planets, as well as for a few subgiant planet-host stars (e.g., Gonzalez 2003, Santos et al. 2003, Fischer & Valenti 2005). In other words, the bulk metallicity enrichment observed most probably reflects the metal content of the cloud of gas and dust that gave origin to the star and planetary system.

It should be mentioned, however, that this perspective is not completely established (e.g., Vauclair 2004), and it is possible that in some cases pollution might have played an important role. Recent asteroseismological observations also keep open the possibility that metallicity gradients (induced by stellar pollution) may exist in one metal-rich planet-host star (Bazot et al. 2005). More measurements are needed in order to completely settle this question.

4.1.2. Metallicity and the frequency of planets. A careful look at the metallicity distribution of planet-host stars shows that the probability of finding a planet is a steeply rising function of the metallicity of the star (see **Figure 9**). More metal-rich stars have a higher probability of harboring a giant planet than their lower metallicity counterparts (Santos, Israelian & Mayor 2001, 2004; Reid 2002; Fischer & Valenti

2005). Current numbers suggest that at least 25% of the stars with twice the metal content of our Sun ([Fe/H] $\geq$ 0.3) are orbited by a giant planet, and this number decreases to below 5% for solar-metallicity objects.

In other words, metallicity seems to play a crucial role in the formation and/or evolution of planets, at least for giant planets of the kind radial-velocity searches have revealed up to now. For the lower mass solid planets, no such trend is observed but the statistics are still poor (see discussion in Section 4.2). The observed metallicity correlation does not imply that giant planets cannot be formed around more metal-poor objects, but rather that the probability of formation among such systems is lower (Rice & Armitage 2003, Ida & Lin 2004a). Indeed, there is some hint (see **Figure 9**) that for lower [Fe/H] values, the frequency of planets may remain relatively constant as a function of the metallicity (Santos, Israelian & Mayor 2004). A power-law fit to the whole data set does not permit fitting the data adequately. Whether this reflects the presence of two different regimes (flat distribution for low metallicities and a strong rise toward higher [Fe/H] values), or simply a low-metallicity tail, is currently under debate.

In this sense, it is interesting to note that a search for transiting planetary companions in the 47 Tuc metal-poor globular cluster has not detected any event (Gilliland et al. 2000, Weldrake et al. 2005). We caution, however, that the extreme environment of a globular cluster might not be the best place for planets to form. Curiously, in **Figure 9** we can also see that the Sun is in the low-metallicity tail of the distribution of planet-host stars. The meaning of this result is not clear, but it will be interesting to observe how the [Fe/H] distribution of exoplanets will behave when, with increasing survey durations, a significant number of real Solar System analogs are found (see also discussion in Laws et al. 2003). Overall, these results will have important consequences on the studies of the frequency of planets in the Galaxy (e.g., Lineweaver 2001).

4.1.3. Implications for models of planetary formation. Two main models of giant-planet formation are now debated in the literature. On one side, the traditional core-accretion scenario (e.g., Mizuno 1980; Pollack et al. 1996; Rice & Armitage 2003; Alibert, Mordasini & Benz 2004) tells us that giant planets are formed by the runaway accretion of gas around a previously formed rocky/icy core with about 10–15 times the mass of Earth. Opposite to this idea, Boss (1997, 2006) (see also Mayer et al. 2002) proposes that giant planets may form by a direct disk instability process. Traditionally, the main advantage of the instability model is the shorter timescales needed to form planets. Although not clear, in the core-accretion model, the formation of a giant planet may take longer than the currently estimated lifetimes of T Tauri disks (e.g., Pollack et al. 1996; Haisch, Lada & Lada 2001). This problem may have been recently solved by the inclusion of migration and disk evolution in the models of planet formation (Rice et al. 2003; Alibert, Mordasini & Benz 2004; Nelson & Papaloizou 2004).

However, the efficiency of planetary formation may not be dependent on the metallicity of the star/disk (Boss 2002), according to the instability model. This is opposite to what is expected from the traditional core-accretion scenario (e.g., Ida &

Lin 2004a, Alibert, Mordasini & Benz 2004), because the higher the grain content of the disk, the easier to build the metal cores that will later-on accrete gas, before the gas disk dissipates. The fact that the probability of finding a giant planet is a strong function of the stellar metallicity thus favors the core-accretion model as the main mechanism responsible for the formation of giant planets (although the disk instability model is not completely excluded). Ida & Lin (2004a), Kornet et al. (2005) and Benz et al. (2006) have even shown that, according to the core-accretion model, it is possible to predict the observed [Fe/H] distribution of planet-host stars.

It should be cautioned, however, that it is not known precisely how an increase in the stellar metallicity may alter the actual gas-to-dust ratio of the protoplanetary disk, nor how it is influencing planetary formation and/or evolution. The mass of the disks themselves (dependent on the stellar mass?) or the timescale of disk depletion for stars with different metallicities, are variables that are not known observationally with enough precision.

4.1.4. The case for other elements. Most spectroscopic studies on the chemical properties of stars with planets have concentrated on measuring the abundances of iron as a metallicity proxy. Now, the number of studies regarding other elemental abundances is increasing. These analyses explored the abundance of a variety of chemical species, from the light elements lithium (Li) and beryllium (Be) (e.g., García, López & Peres de Taoro 1998; Deliyannis et al. 2000; Gonzalez & Laws 2000; Ryan 2000; Gonzalez et al. 2001; Santos et al. 2002, 2004b; Israelian et al. 2004; Chen & Zhao 2006; Luck & Heiter 2006), up to alpha and iron-group elements (e.g., Sadakane et al. 1999, 2002; Santos, Israelian & Mayor 2000; Gonzalez et al. 2001; Smith, Cunha & Lazzaro 2001; Takeda et al. 2001; Zhao et al. 2002; Bodaghee et al. 2003; Ecuvillon et al. 2004a,b, 2006a; Beirão et al. 2005; Fischer & Valenti 2005; Takeda & Honda 2005; Bond et al. 2006; Gilli et al. 2006; Luck & Heiter 2006; Santos et al. 2006b), and have unveiled a few interesting trends (especially for lithium—Israelian et al. 2004, Chen & Zhao 2006). In general, though, these studies suggest that stars with giant planets are just the metal-rich extension of the galactic disk population.

The study of other elements might, however, be of great importance. For example, if pollution of the stellar atmosphere is common among planet-host stars (or any field or cluster star, e.g., Murray et al. 2001; Quillen 2002; Wilden et al. 2002; Laws & Gonzalez 2003; Paulson, Sneden & Cochran 2003; Dotter & Chaboyer 2003; Desidera et al. 2006; Randich et al. 2006), we can expect to find these stars to be more enriched in refractory elements, because volatiles could evaporate from infalling bodies before being accreted (e.g., Gonzalez 1998; Smith, Cunha & Lazzaro 2001; Ecuvillon et al. 2006b). In case of accretion, we can further expect planet hosts to present overabundances of elements that are not supposed to exist in great quantities in the star, but are abundant in the planets and planetary material. This is the case for ^{6}Li, whose detection is claimed for the planet-host star HD 82943 (e.g., Israelian et al. 2003).

The abundance of particular elements may also be essential to form the cores of giant planets (e.g., Robinson et al. 2006). An overabundance of these species could thus increase the planetary formation efficiency. Up to now, however, no clear global evidence of differences between elements of different condensation temperatures have been found regarding any of these matters (e.g., Smith, Cunha & Lazzaro 2001; Takeda et al. 2001; Ecuvillon et al. 2006b).

4.1.5. Metallicity and orbital elements. Hints of trends between the metallicity of the host stars and the orbital parameters of the planets have been discussed (Gonzalez 1998; Queloz et al. 2000; Santos et al. 2003, 2006a; Sozzetti 2004). Stars with short-period planets (i.e., small semimajor axes) may be particularly metal-rich, even among planet hosts. Although the results are clearly not significant, such a correlation could be supported by theoretical models, because migration mechanisms could either induce pollution of the stellar atmosphere (e.g., Lin, Bodenheimer & Richardson 1996) or depend on the quantity of planetesimals in the disk (e.g., Gonzalez 1998; Murray et al. 1998; Del Popolo, Gambera & Ercan 2001).

The observed metallicity excess could even be inherent to planets that have migrated sufficiently to become detectable in the baseline of measurements of the current radial-velocity surveys (Gonzalez 2003). The most recent models suggest, however, that Type II migration should not be very dependent on the metallicity of the disk (Livio & Pringle 2003). According to the recent results of Ida & Lin (2004b) and Benz et al. (2006), a higher metallicity will permit the formation of giant planets faster and/or closer to their host star (even inside the ice boundary). Their faster formation will give them more time to migrate, thus explaining a putative correlation between metallicity and orbital period. A fast migration rate could dilute this effect.

Relations between the stellar metallicity and other planetary orbital parameters have also been explored, namely with the eccentricity, orbital separation, and planetary minimum mass (Laws et al. 2003, Santos et al. 2003, Fischer & Valenti 2005). Again, no significant trends have been found, although hints for some possible correlations have been pointed out. In the planet-mass regime below $\sim$20 M_{Jup} (the range discussed in this review), no clear metallicity differences seem to exist between stars having companions with masses either above or below 10 times the mass of Jupiter (e.g., Santos et al. 2003). A difference could be expected if these two populations had known different formation processes (Rice et al. 2003).

As new planets are added to the list, it will definitely be interesting to follow the results and redo all the analyses. This is particularly true when Solar System analogs will be found, with Jupiter-mass planets in long-period, circular orbits.

4.2. Metallicity of Stars with Neptune-Mass Planets

The well-known strong correlation between the presence of planet and the stellar metallicity that exists for stars hosting giant planets does not seem to be present for their lower mass counterparts (Udry et al. 2006). The Neptune-mass planets found so far have a rather flat metallicity distribution. This conclusion is strengthened by the fact that a significant portion of them have been found thanks to follow-up studies of (metal-rich) stars already known to harbor giant planets (e.g., Santos et al. 2004a, McArthur et al. 2004), a fact that should have biased the sample toward higher metallicities. Moreover, considering systems with only hot Neptunes (without any other

Jupiter mass analog), though the number is still small, the metallicity distribution becomes slightly metal-poor.

This observational result is supported by recent planet-formation models based on core accretion. Ida & 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 Earth. The metallicity distribution of stars hosting Neptune-mass planets then brings further support for the core-accretion model.

We should note at this point that a significant percentage (∼40%) of the stars with Neptune-mass planets are M dwarfs. The metallicities for these stars are somewhat uncertain. Recent efforts are under way to derive accurate stellar metallicities for these objects (Bonfils et al. 2005b; Bean, Benedict & Endl 2006; Woolf & Wallerstein 2006), and the situation may change in the upcoming years.

4.3. Effect of Stellar Masses

Another parameter whose influence on the giant planet frequency has been explored is stellar mass. Although limited, the results of the current surveys suggest a slight tendency for higher mass stars (up to $\sim 1.5\ M_\odot$) to have a higher frequency of planets (Laws et al. 2003). Given the limitations inherent to the radial-velocity technique, the stellar mass range explored by most radial-velocity planet-search programs is quite small (FGK dwarfs, ranging from roughly 0.7 to 1.3 $M_\odot$). Together with the inherent uncertainties in the grids of theoretical models (e.g., Fernandes & Santos 2004), this strongly limits the conclusions of any study of the mass-frequency correlation for exoplanets.

Examining a potential link between primary masses and orbital periods, Burkert & Ida (2007) suggest, from the observation and modeling points of view, that the shortage of planets with semimajor axes in the range of 0.1–0.6 AU (periods of ∼10–100 days, see Section 2.3) results from a gap in the radial distribution of planets orbiting stars with masses above 1.2 $M_\odot$. A possible explanation for this trend invokes shorter depletion timescales (early stop of migration) for disks around stars more massive than 1.2 $M_\odot$ than for those around less massive stars. Strong UV radiation from massive (pre-Main Sequence) stars may also inhibit migration out to a few AUs.

To address the raised issues, a few projects searching for planets around higher mass stars are currently in progress. These include programs to search for planets around A–F dwarfs (Galland et al. 2005a) as well as specific programs to search for planets orbiting giant, intermediate-mass stars (e.g., Sato et al. 2003, Hatzes et al. 2005, Setiawan et al. 2005). Given that these surveys are more sensitive to the detection limits of the radial-velocity technique, to our knowledge no clear results about the frequency of planets around these stars has been published yet.

Interestingly, for intermediate-mass stars hosting giant planets, the existence of a metallicity–giant planet correlation is not clear (da Silva et al. 2006). The balance between the stellar metallicity and mass effect is probably not easy to disentangle.

At the opposite stellar mass regime, a similarly dedicated effort is being made to search for planets around M dwarfs (e.g., Bonfils et al. 2005a, Endl et al. 2006). Although the number of planets orbiting such stars is not very large yet, the most recent data suggest that giant planets may be sparser around M dwarfs, at least in the short-period range (e.g., Bonfils et al. 2006, Endl et al. 2006). This result is expected according to some planet-formation models (Laughlin, Bodenheimer & Adams 2004), although a consensus does not exist at this point (Kornet, Wolf & Róyczka 2006; Boss 2006). However, current results suggest that Neptune-mass planets in short-period orbit may be common around these stars (Bonfils et al. 2007).

4.4. Other Results on Planet-Host Stars

A relationship between stellar metallicity and galactic dynamics of stars with planets has also been explored by some researchers (Gonzalez 1999, Reid 2002, Barbieri & Gratton 2002, Santos et al. 2003). Ecuvillon et al. (2007) show that stars with giant planets have typical kinematical properties of metal-rich stars in the Solar Neighborhood. They suggest that these stars could have been formed in the inner disk of the Galaxy, and then migrated outward because of the effect of the galactic bar (see also Famaey et al. 2007). This hypothesis could help to explain preliminary results suggesting that nearby star-forming regions are not metal-rich (e.g., James et al. 2006).

Barnes (2001) and Saffe, Gómez & Chavero (2005) looked for possible correlations between the presence of planets and chromospheric activity levels, ages, and rotational periods of host stars. They did not find any clear evidence that stars with planetary companions discovered by radial-velocity surveys differ from average field stars. Suchkov & Schultz (2001) have further compared the ages of F dwarfs with planets with the ages of Hyades and field F dwarfs. Their analysis suggests that F dwarfs with planets have ages similar to those derived for the Hyades. All researchers point out that current planet-search surveys are mostly based on low-activity objects (for which the measurement precision is better). This introduces biases in the samples that are difficult to take into account.

Melo et al. (2006) have also explored the ages of stars with transiting planets discovered by deep transit surveys like OGLE (Udalski et al. 2002a,b). The results, based on both Ca II activity index and lithium abundances, provide lower limits for the derived ages above 0.5 Gyr.

Interesting studies point out that planet-induced stellar chromospheric activity may be observed in some cases (see Shkolnik, Walker & Bohlender 2003 and references therein). This might be the result of tidal interactions between the planet and the star, or of the interaction between the magnetic fields of the star and the planet (Rubenstein & Schaefer 2000; Cuntz, Saar & Musielak 2000).

Finally, a few researchers have tried to search for the signature of debris disks around planet-harboring stars (e.g., Greaves et al. 2004, Beichman et al. 2006, Moro-Martín et al. 2007), as well as for radio emission (e.g., Bastian et al. 2000, Stevens 2005) originating from the planets. The results are not conclusive at this time.

5. TRANSITING PLANETS

So far, most of the known extrasolar 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 obtained about the planetary physical properties, like their true masses, radii, and mean densities. Such additional information is however available in the case of planetary transits. Until recently, however, it had been possible in only a few cases 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 are starting to deliver interesting results, giving a new breath to the study of exoplanets. Several candidates have been announced by different surveys, the most prolific up to now being the OGLE campaign, which announced close to 180 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 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. 2005a, Pont et al. 2005). Finally, only 5 candidates have been confirmed as planets in transit among the 177 OGLE candidates. The spectroscopic follow up thus demonstrated the difficulty of the interpretation of shallow transit light curves without complementary radial-velocity measurements. The magnitude of the OGLE planetary candidates ranges from $V \sim 16$ to 17.5, close to the faint capability of accurate fiber-fed spectrographs on large telescopes (as, e.g., FLAMES on the VLT), the most suited instrumentation for this purpose. This implies that deeper photometric transit surveys are facing serious difficulties in confirming the planetary nature of the transiting objects by Doppler follow up. For example, a recent HST survey for planets around stars in a stellar field toward the Galactic bulge has yielded 16 planet candidates (Sahu et al. 2006), some with unprecedented very short-period orbits (<1 day). However, except in maybe one case, no radial-velocity confirmation is possible for these very faint stars ($V \geq 20$). In this review we thus prefer not to consider these candidates for the statistical discussion.

In 11 cases from brighter surveys, however, the planetary nature was confirmed by follow-up radial-velocity measurements (Konacki et al. 2003; Alonso et al. 2004; Bouchy et al. 2004; Pont et al. 2004, 2005; McCullogh et al. 2006; O'Donovan et al. 2006; Bakos et al. 2007; Collier Cameron et al. 2007). Together with the three transiting planets first discovered in radial-velocity surveys (Charbonneau et al. 2000, Sato et al. 2005, Bouchy et al. 2005b), the 14 known transiting extrasolar 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 permitted us access to the atmospheres of these worlds, giving important clues about the physics of these atmospheres (Charbonneau et al. 2002). The planet orbiting HD 209458 was found to have an exosphere, with C and O atoms being hydrodynamically carried by the evaporating H atmosphere (Vidal-Madjar et al. 2003, 2004). Finally, the detection in the infrared of the antitransit (when the planet passes behind the star) of the planets orbiting HD 209458, HD 189733, and TrES-1 (Charbonneau et al. 2005, Deming et al. 2005, 2006), as well as of photometric phase variations of υ and b (Harrington et al. 2006), provides us with the possibility to determine a first planetary coarse-resolution spectrum and to understand the temperature distribution on the planet. The results suggest that short-period planets may have distinct hot (day) and cold (night) faces.

The new detections have also raised a lot of scientific problems and questions. For example, about one-half of the transiting planets discovered by the OGLE campaign (Konacki et al. 2003, Bouchy et al. 2004) have orbital periods of the order of 1–2 days. This result is in clear contrast with the known lower limit around 2.5 days observed for hot Jupiters detected by the radial-velocity technique. Whether this is simply the result of a photometric detection bias or if this can be partly explained by some other physical process (e.g., very short-period planets could be young, and did not have time to evaporate) has been debated. Current results suggest indeed that ground-based transit surveys are strongly biased toward the discovery of very short-period planets, the latter being then less frequent than standard hot Jupiters (Gaudi, Seager & Mallen-Ornelas 2005). Support for this comes from the fact that the stars with very short-period planets do not seem to be younger than 0.5 Gyr (Melo et al. 2006).

Many other interesting issues have also been raised. For example, the planets have a large diversity of mean densities, some of them anomalously low, below one-half to one-third the density of Jupiter (see **Figure 10**). Two particularly clear cases are the planet orbiting HD209458 (Charbonneau et al. 2000) and the recently announced planet HAT-P-1b (Bakos et al. 2007), with large radii for their masses. This oversizing is difficult to explain by present models of planet structure and requires the inclusion of some extra physical processes to supply the needed internal energy (e.g., Guillot 2005, Levrard et al. 2007). Curiously, the planets that have shorter periods also have the highest masses (Mazeh, Zucker & Pont 2005, Collier Cameron et al. 2007). This puzzling observation could be the consequence of mechanisms such as thermal evaporation (Lecavelier des Etangs et al. 2004; Baraffe et al. 2004, 2005) or Roche limit mass transfer (Ford & Rasio 2006), although a clear explanation does not exist yet.

Finally, recent studies indicate the existence of a correlation between stellar metallicity and planetary structure (Guillot et al. 2006), in the sense that planets orbiting more metal-rich stars also have higher mass cores (see also Burrows et al. 2007). This trend, if confirmed, may give important constraints to the processes of planetary formation and evolution.

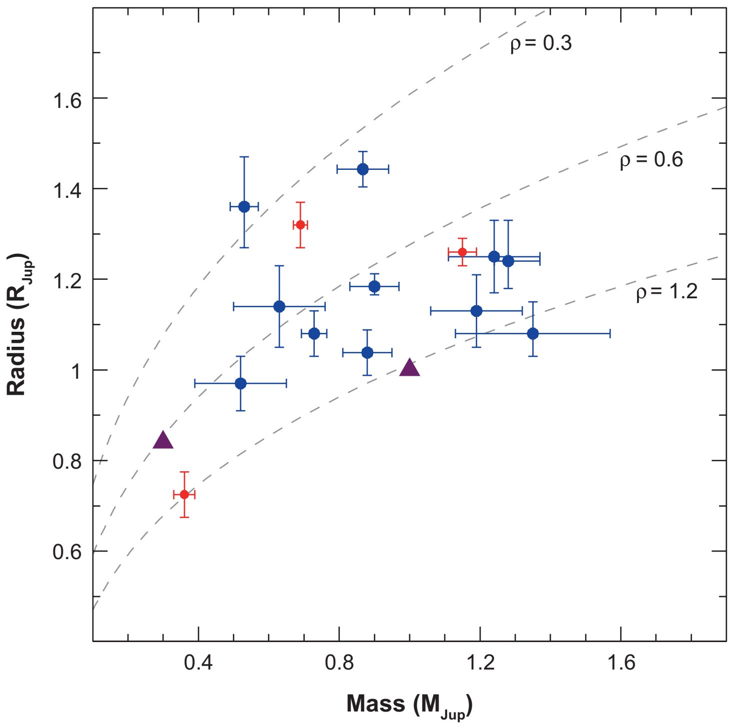


Figure 10

Mass-radius diagram for the known transiting planets. Red points denote planets discovered in the context of radial-velocity surveys, whereas blue points represent those planets discovered in transit searches. Three iso-density curves are also shown for mean densities of 0.3, 0.6, and 1.2 g cm^{-3}. The triangles denote the positions of Jupiter and Saturn. The data used in this plot were taken from the updated tables available at **http://www.exoplanets.eu/transits/TRANSITS.htm**. See this Web page and the text for more references.

6. FUTURE ISSUES

As seen in previous sections, the study of the statistical properties of exoplanets, as well as of their host stars, is now providing important clues about the processes of planetary formation and evolution. Slowly, we are building a new paradigm. From this point of view, a whole new window will be opening during the next few years, as new and more precise surveys will produce their first results. These will increase dramatically the number and observed diversity of known planets, and give us then more information about the actual properties of exoplanets and the way they form.

6.1. Radial Velocities

An important lesson from the past few years is that the radial-velocity technique has not yet reached its limits in the domain of exoplanets. In fact, the future of radial-velocities is quite bright.

Current surveys, including between 3000–4000 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 a 1 m s^{-1} precision or better, as well as new projected high-resolution spectrographs for the new generation of Extremely-Large Telescopes (e.g., Pasquini 2006), will certainly play an important role. Among other things, these will give the opportunity to find even lower mass planets, explore the formation of giant planets at the low stellar mass end, and find systems more similar to our own Solar System. As the time span of the measurements is increased, longer period planets will be unveiled, increasing the extrasolar planet statistics for orbital periods of several years. 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). In such cases, 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 also indicate that a population of Neptune- and Saturn-mass planets remains to be discovered below 1 AU. With the level of precision now achieved for radial-velocity measurements, a new field in the search for extrasolar planets is open, allowing the detection of companions of a few Earth masses around solar-type stars. Very low-mass planets ($<10\ M_{\oplus}$) might be more frequent than the previously found giant worlds.

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 m s^{-1} level. Results obtained with the HARPS spectrograph show that, even if stars are intrinsically variable in radial velocity (at different levels) owing to acoustic modes, it is nevertheless possible to reach a short-term precision well below 1 m s^{-1} (10 cm s^{-1}?) by applying an adequate observational strategy (**Figure 2**). One issue remains however unsolved: the behavior of the stars on longer timescales, where stellar jitter and spots may impact the final achievable accuracy. In this case, an accurate preselection 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. An enlightning example of the potential of this approach is given by the longer period planet in the HD 69830 system (Lovis et al. 2006) for which residuals as low as $\sim$20 cm s^{-1} are measured around the solution (after removing the two shortest period planets), when the measurements are averaged over week-long observing runs.

6.2. Photometric Transits

Other techniques are also providing the possibility to find planets around other stars. Interestingly, as happens when observing the Universe at a different wavelength, changing the technique gives us access to a sometimes completely different parameter space (e.g., different planet and stellar masses or orbital radii).

Photometric transit searches are among the most promising. 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 14 known transiting planets are opening a new window to the study of the properties of the exoplanets themselves, such as their density or atmospheric composition and structure.

In this domain, further (and higher) expectations are coming from space-based instruments like *Convection, Rotation & Planetary Transits* (COROT) or *Kepler* (more information on these missions is available at **http://smsc.cnes.fr/COROT/** and **http://www.kepler.arc.nasa.gov/**, respectively). Out of Earth's atmosphere, these satellites will achieve a photometric precision better than 0.01%, permitting the detection of transiting Earth-sized planets, largely expanding the study of planet physical properties toward very low masses. For these small-sized 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, O'Connell & Sasselov 2006; Fortney, Marley & Barnes 2007). If one considers a transit signal with a 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-$M_{\oplus}$ planet on a 4-day orbit induces a radial-velocity amplitude of about 80 cm s^{-1} that will be possible to detect with only a 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.

6.3. Astrometry

From the astrometric point of view, the expectations are not lower. Instruments like the HST and the JWST in space or the VLTI and the Keck interferometer from the ground 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* or the *Space Interferometry Mission* (SIM) are expected to completely change the current landscape by adding thousands of new planets or pushing down the detection limits toward very low-mass planets. Given that astrometry is more sensitive to longer period systems, 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 finding planets around targets not accessible with radial-velocity surveys, like A or B stars, or T Tauri stars.

6.4. Stellar Properties

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. 2005, 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). This 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).

6.5. Toward the Future

Another important challenge in the field is that of directly imaging a planet orbiting a solar-type star. This task is not easy, however. Planets are cold bodies, and the planet/stellar luminosity ratio is of the order of 10^{-9} (in the visible). Seen from a distance of a few parsecs, a planet is no more than a small undetectable dot embedded in the stellar diffraction image. Current adaptive-optics instrumentation are already giving us the first images of very low-mass companions to close-by young stars (Chauvin et al. 2005, Neuhäuser et al. 2005). The development of a new generation of adaptive-optics systems, such as SPHERE (the VLT Planet Finder) or the Gemini Planet Imager (Beuzit et al. 2007), promises a great improvement in this field.

All these elements will permit us to better understand the mechanisms leading to the formation of planetary systems like our own, and will thus represent an important step toward 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 toward this specific goal: the space interferometers *Darwin* (ESA) and 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 the very near future, humanity has to prepare itself to find out that the whole Universe may be teeming with life.

ACKNOWLEDGMENTS

This review has greatly benefited from lively and thoughtful comments and discussions with many key players in the field. Special thanks goes to M. Mayor, Y. Alibert, W. Benz, A. Burkert, E. van Dishoeck, D. Fischer, G. Israelian, D. Latham, T. Mazeh, R. Nelson, F. Pepe, D. Queloz, R. Rebolo, D. Sasselov, and many others. We thank the Swiss National Science Foundation (FNRS) and the European RTN "The Origin of Planetary Systems" (PLANETS, contact number HPRN-CT-2002-00308) for their support. Support from the Fundação para a Ciência e a Tecnologia, Portugal (fellowship SFRH/BPD/8116/2002 and grant POCI/CTE-AST/56453/2004), and from the HELAS Network (fellowship CAUP-03/2007-BDCG) is gratefully acknowledged.

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Annual Review of Astronomy and Astrophysics

Volume 45, 2007

Contents

An Accidental Career
Geoffrey Burbidge 1

The Beginning of Modern Infrared Astronomy
Frank J. Low, G.H. Rieke, and R.D. Gehrz 43

Infrared Detector Arrays for Astronomy
G.H. Rieke 77

Heating Hot Atmospheres with Active Galactic Nuclei
B.R. McNamara and P.E.J. Nulsen 117

Physical Properties of Wolf-Rayet Stars
Paul A. Crowther 177

The Search for the Missing Baryons at Low Redshift
Joel N. Bregman 221

Irregular Satellites of the Planets: Products of Capture in the Early Solar System
David Jewitt and Nader Haghighipour 261

A New View of the Coupling of the Sun and the Heliosphere
Thomas H. Zurbuchen 297

Cold Dark Clouds: The Initial Conditions for Star Formation
Edwin A. Bergin and Mario Tafalla 339

Statistical Properties of Exoplanets
Stéphane Udry and Nuno C. Santos 397

Relativistic X-Ray Lines from the Inner Accretion Disks Around Black Holes
J.M. Miller 441

Toward Understanding Massive Star Formation
Hans Zinnecker and Harold W. Yorke 481

Theory of Star Formation
Christopher F. McKee and Eve C. Ostriker 565