2 The Diversity of Extrasolar Planets Around Solar Type Stars

Stéphane Udry and Michel Mayor

An important step in the search for an environment favorable to the development of exobiological life was accomplished in 1995 with the discovery by Mayor and Queloz [1] of the first extrasolar planet orbiting a star similar to the Sun, 51 Pegasi. As the proximity of the planet to the star and the large luminosity contrast between the star and the planet prevent the planet to be seen directly, its presence was inferred from the induced modulation of the observed stellar radial velocity. This method provides interesting information on the orbital characteristics of the system, although giving only access to the minimum mass of the planetary companion (projection effect due to the non-alignment of the orbital plane with the line of sight). Nevertheless, the radial-velocity technique, whose precision allows giant-planet detections, has proven since then to be very efficient. During the past 6 years an impressive series of new enthusiastic results in the domain were announced. New candidates are regularly pointed out by the teams of «planet hunters» monitoring high-precision radial velocities. Also a number of various approaches to the field are explored aiming to better understand and constrain planetary formation.

The new detected candidates present a large variety of characteristics, often unexpected from the observation of our own Solar System: some of the giant planets are found very close to their parent stars (a few stellar radii), some are on very elongated orbits, some of the planets are also very massive. In fact, new observational results often tend to set new questions rather than bring definitive answers to the large variety of extrasolar system properties. However, the regular increase of candidate discoveries already allows us to point out some preliminary trends that should help us to better understand the formation of extrasolar planets.

The goal of this presentation is to give to the readers a synthetic, up-to-date view of the field, keeping in mind that it is evolving very rapidly. The main milestones of exoplanet discoveries will be recalled, with a special emphasize on the most recent announcements of the Geneva group. The global properties of the extrasolar planet sample as a whole will be discussed as well. The second part of this contribution will be devoted to a global description of the extrasolar planet properties in terms of mass function and orbital element distributions, emphasizing their differences from the equivalent distributions for stellar companions to solar type stars. Giant planets and stellar binaries have different formation mechanisms whose fossil traces should be revealed by a comparison of their orbital characteristics. Chemical properties of stars with planets will then be discussed in comparison with stars without known planets. Finally, future ambitious programs aiming to search for terrestrial planets and signature of life in their atmospheres will be mentioned.
2.1 Detections: Milestones and Recent Announcements

It is not possible in a few lines to give an exhaustive report of the extremely rich ensemble of results obtained during the past years in the domain of extrasolar planets. We will simply recall the main prominent discoveries of the past 6 years, with a special mention to the latest news.

1995: A pioneer Canadian team around G. Walker published their negative results from a high-precision radial-velocity systematic search for giant planets, carried out over more than 10 years, in a sample of 21 solar type stars [2].

October 1995: Mayor and Queloz [1] announced the detection of the first extrasolar planet orbiting a solar type star, 51 Pegasi. The discovery came from a systematic radial-velocity monitoring of 142 dwarfs of the solar neighborhood, started with ELODIE at the Haute-Provence Observatory 1.5 years earlier. The very exotic properties of the planet ($P = 4.23$ days, $a = 0.05$ AU, $T_{eq} \approx 1300$ K) raised interesting questioning on the standard views of planetary formation.

1996: At Lick, G. Marcy and P. Butler, following a sample of 120 stars, rapidly announced 5 more candidates among which 3 presented properties similar to 51 Peg b [3].

1998: Summer 1998, 8 planets were known [4]. At the end of the same year, 16 planets were known. The acceleration of the discoveries was due to the growing time base of the observations and to an enlargement of the monitored samples.

April 1999: Twenty planets had been detected, among them the first multi-planet system, $\upsilon$ And (Andromeda) [5]. Two years after the discovery, the proposed 3-planet model always fits the observations very well [6]. The 3 planets have periods of 4.6, 241 and 1308 days, and minimum masses of 0.68, 2.05 and 4.29 $M_{\text{Jup}}$, respectively.

November 1999: Announcement of the transit of a planet in front of the stellar disk of HD 209458. From the photometric data [7, 8] the real mass, radius and mean density of the planet have been determined [9]. Information on the system geometry was also inferred from the spectroscopic observations of the transit [10].

Spring 2000: Discoveries of several planetary candidates with minimum masses below the mass of Saturn [11, 12].

August 2000: Nine new planetary candidates were announced at the IAU Symp. 202 in Manchester (IAU General Assembly), among them the second and third known multi-planet systems: HD 83443 harboring 2 subsaturn-mass planets close to their parent star [13] and HD 168443 a system with a massive inner planet and a still more massive very low-mass companion further out [14]. HD 83443 seems to be a resonant system with a ratio of 10 between the periods.

January 2001: A new stunning 2-planet resonant system is proposed to model the radial velocities of Gl 876 [15], for which the single-planet model left large residuals around the Keplerian solution [16, 17]. The periods of the 2 planets are found to be close to a ratio of 2.

March 2001: Very recently, 11 new planetary candidates including 2 new multi-planet systems have been announced by the Geneva group and international collaborators [18]. Several of the candidates present interesting properties. They will be briefly described in the following part as well as the two new multi-planet systems, HD 74156 and HD 82943.
In summary, beginning of May 2001, 63 objects are known with minimum masses below 10 Jupiter masses (or 67 with $m_2 \sin(i) < 17 \text{M}_{\text{Jup}}$; Table 2.1). Among them, 6 multi-planet systems have been detected. Taking into account that the large on-going planet-search programs are still incomplete and inhomogeneously followed, we can estimate the fraction of the sample stars with giant planets to be larger than 5%. A more definitive estimate will become available with the completion of the large surveys of statistically well-defined samples as e.g., the CORALIE planet-search program in the Southern hemisphere [19].

**Fig. 2.1** Visual drawing of some of the newly detected extrasolar planets (top left). Radial-velocity measurements and best Keplerian solutions for HD 80606 (bottom right) and the 2-planet systems HD 82943 (top right) and HD 74156 (bottom left); HJD=Heliocentric Julian Date; RV=Radial Velocity.
Table 2.1. Main orbital characteristics of the exoplanets and very low-mass brown dwarfs. The list is sorted by increasing minimum masses.

<table>
<thead>
<tr>
<th>Object</th>
<th>$P^{1)}$ (days)</th>
<th>$e^{2)}$</th>
<th>$m_2\sin(i)^{3)}$ ($10^{-3} M_{\text{Sun}}$)</th>
<th>$A^{4)}$ (AU)</th>
<th>References</th>
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Table 2.1. Main orbital characteristics of the exoplanets and very low-mass brown dwarfs. The list is sorted by increasing minimum masses (continued)

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<th>Object</th>
<th>( P ) (^{1)} ) (days)</th>
<th>( e ) (^{2)} )</th>
<th>( m_2\sin(i) ) (^{3)} ) (10(^{-3}) ( M_{\odot} ))</th>
<th>( A ) (^{4)} ) (AU)</th>
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<td>( \tau ) Boo</td>
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<td>( \nu ) And d</td>
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\(^{1)} P=Period; \(^{2)} e=orbital eccentricity; \(^{3)} m_2=mass of the planet, m_2\sin(i)=minimum mass of the planet; \(^{4)} a=semi-major axis

2.2 Very Recent ELODIE and CORALIE Detections

ELODIE and CORALIE are two high-resolution spectrographs designed for high-precision radial-velocity measurements [20]. They are installed on the 193-cm telescope at the Haute-Provence Observatory (France) and on the 1.2-m Leonard Euler Swiss telescope at La Silla Observatory (ESO, Chile), respectively. The ELODIE planet-search sample is magnitude-limited and consists of \(~350\) F-K dwarfs of the solar vicinity. It is an extension of the original \(Mayor-Queloz\) sample out of which 51 Peg b was discovered [1]. The CORALIE planet-search sample consists of more than 1650 F8
to M0 solar type stars selected according to distance in order to obtain a statistically well-defined volume-limited set of dwarfs of the solar neighborhood [19]. In addition to the planet search, this sample will allow us to collect information on spectroscopic binaries and give us a synthetic view on companions to solar type stars from $q=m_2/m_1=1$ down to $q \leq 0.001$.

On April 4th 2001 [18], we announced the latest results related to these two programs, namely the detection of 11 new planetary candidates, among them two multi-planet systems. Their main orbital properties are given in Table 2.1. Some have special characteristics:

- The 2-planet system around the star HD 82943 [18] (Fig. 2.1, top right) is resonant in the same way as Gl 876 [15]: the period of the inner planet (221.8 days) is almost exactly half of that of the outer one (443.7 days). Future observations should confirm the 1:2 ratio between the periods. Gravitational interactions between the two planets are expected to be strong. Consequently, a two-Keplerian model will rapidly diverge from the real temporal evolution of the system, requiring new developments for investigating those systems [21].

- The 2-planet system HD 74156 [18] is reminiscent from HD 168443 [14] with a Jupiter-size planet on a 51.6-day period orbit and a second, heavier companion further out. The outer period is estimated to be around 2300 days from the minimization of the residuals around the solution (Fig. 2.1, bottom left). The long period is not completely covered yet and could be somehow larger than the estimated value. In such a case however, the inferred minimum mass of $7.4 \, M_{\text{Jup}}$ for the outer planet will not change much as its dependency with the orbital period is very weak. Such systems set the question of the possible formation of super-massive planets in protoplanetary disks.

- The orbit of HD 28185 b [18, 22] is very nearly circular and its period of 385 days completely locates the planet in the “habitable zone” of the central star, at a distance of 1.007 AU, almost exactly the Earth-Sun separation. The giant, gaseous nature of the planet (minimum mass of $5.6 \, M_{\text{Jup}}$) seems not favorable for the development of life on its surface. However, moons potentially orbiting the planet may well harbor more bio-friendly environments. The hypothesis of natural satellites around giant extrasolar planets is not so speculative when observing our own Solar System.

- HD 80606 b [18, 23] is the planet with the most elongated orbit detected so far ($e = 0.927$; Fig 2.1, bottom right). This star was followed in the framework of an ELODIE/HIRES-Keck collaboration involving the Geneva, Grenoble, Haute-Provence Observatories, the CfA and the Tel Aviv University. Along its orbit, the planet explores a region between 0.034 AU (a few stellar radii) and 0.905 AU from the star. The origin of the elongated shapes of most of the long-period exoplanetary orbits is far from being fully understood yet (see below). A number of them, including the present candidate, could owe their large eccentricities from the dynamical perturbation of an additional stellar or planetary companion. HD 80606 belongs to a visual double system with a similar star, HD 80607, 1800 AU apart.

With these 11 new discoveries the CORALIE/ELODIE programs have contributed to the detections of 32 among the 63 known planetary candidates with minimum masses below 10 Jupiter masses (or 36 among the 67 objects with $m_2 \sin(i) < 17 \, M_{\text{Jup}}$).
Furthermore, among the new detections we have 2 new planetary systems bringing to 6 the number of known multi-planet systems, 4 of which (with HD 83443 [13] and HD 168443 [14]) owe their detection to CORALIE/ ELODIE measurements. This demonstrates the outstanding role that small-size telescopes can still play in modern astrophysics.

2.3 Observed Properties of Extrasolar Planets

The observed properties of planetary candidates are diverse and often surprising because different from the characteristics of the giant planets of our Solar System. A visual idea of the global properties of the sample is given in Fig. 2.2 displaying the eccentricities of the planet orbits as a function of the star-planet separations. The symbol sizes scale with the planet minimum masses inferred from the Keplerian orbital solutions.

![Figure 2.2](image)

**Fig. 2.2** Separation–eccentricity diagram for the sample of known extrasolar planets and very low-mass brown dwarfs. The dot size is related the the minimum mass of the objects. Components of multi-planet system are connected by dotted lines.

The figure is interesting. It clearly shows several of the unexpected properties of
extrasolar planets. From the observation of our Solar System we were expecting Jupiter-like planets on quasi-circular orbits with periods of the order of several years. We have actually found planets with minimum masses up to ten times the mass of Jupiter, often on elongated orbits and with periods that can be very short, of the order of a few days. These different aspects will be discussed in the following parts. A more extended review of the extrasolar planet properties can be found e.g., in the PPIV contribution of Marcy, Cochran and Mayor [24].

In figure 2.2 the components of multi-planet systems are connected by dotted lines. As for single-detected planets, they present a large variety of characteristics: well hierarchized systems, resonant planets, very light or super-massive components. Except for HD 83443, there seems to be a trend for the outer planets to be more massive than the inner ones. This is most probably due to an observational bias, inherent to the radial-velocity technique more sensitive to closer and heavier planets. Multi-planet systems are still sparsely detected, but their number will grow rapidly with the increasing time-base and precision of the surveys. Already in a sample of 12 stars with planets, followed over more than 2 years at Lick, half of the stars present a drift of their systemic velocity, indicating the presence of an additional planetary or stellar companion [25].

2.4 Hot Jupiters

Thirteen among the extrasolar planets detected to date reside in close orbits, with $a < 0.09$ AU. Such small orbits were not predicted by the standard theory (e.g., [26-28]). The surprising small orbits stand in apparent contrast to the prediction that the giant planets formed first from ice grains, which exist only beyond $\sim 3-5$ AU. Such grain growth provides the supposed requisite solid core around which gas could rapidly accrete, over the lifetime of the protoplanetary disk ($\sim 10^7$ years). In the inner regions where volatiles elements are swept out by the radiation of the newborn star, only “light” objects ($\leq 1 M_{\text{Earth}}$) can form from the remaining material (dust, silicates, etc.).

According to this picture, giant planets should form in the outer regions of the protostellar nebula and then move towards the system center where they are actually observed. Such a migration was already predicted in the early eighties from numerical simulations of gravitational disk-planet interactions [29-31]. The model has been improved now with the newly-formed core rapidly moving inwards and the planet growing by accretion during the migration process [32]. The migration time scale is found to be very short, of the order of $10^6$ years. The difficulty is then to stop the migrating planet before it falls into the central star. Several processes may be invoked (see [33] for a review):

- A central magnetospheric cavity around the star, free of material, extending out to the stellar corotation, at the edge of the disk (magnetic coupling between the star and the disk) [34]: the migration naturally stops at the disk edge.
- Consecutive formation of giant planets that migrate and fall into the star. When the disk disappears some of the planets are still there.
- Exchange of angular momentum between the star and the planet by tidal interaction [35] or mass transfer through Roche lobe overflow [36] when the planet comes close to the star.
Planet evaporation. It takes place when the thermal velocity of the gas (mainly Hydrogen) becomes important with regards to the escape velocity from the planet, typically for $V_{\text{esc}} / V_{\text{therm}}$ smaller than about 5 [37]. This ratio depends mainly on the planet mass and the lighter candidates come close to the evaporation limit [33]. In the future, if some gaseous giant planets on short-period orbits are detected with masses well below 0.2 $M_{\text{Jup}}$, they will be subjected to evaporation-related evolution. We can speculate that these objects will have Hydrogen-depleted atmospheres.

An observational evidence for a stop of the planet migration at a “well-defined” distance from the star is given by the sharp cut-off at the lower end of the cumulative distribution of exoplanet periods (see below, Fig. 2.5 left).

Other scenarios, not involving planet migration, are also proposed for explaining hot Jupiters:

- **Jumping Jupiters**: Several giant planets, formed simultaneously in the protoplanetary disk, perturb each other [38, 39]. These gravitational, chaotic interactions modify their orbital characteristics. Some of the planets may be ejected from the system, some are brought close to the central star. It seems however difficult with this process to bring planets on short-period circular orbits. On the other hand, some close-in planets are found on elongated orbits.

- **In situ formation**: Planets form where they are observed, much more rapidly than generally assumed, in a standard way [40, 41] or from gravitational instabilities in the disk leading to a fast collapse [42]. The perturbation of a close stellar companion could favor such instabilities.

### 2.4.1 Hot Jupiters: Direct Detections

It is possible to take advantage of the proximity of hot Jupiters to their parent stars to directly “see” their presence. Several methods have been proposed.

**Transit.** Short-period giant planets have a significant probability for their orbital plane to be sufficiently close to the line of sight to observe an eclipse of the star by the planet (transit). The probability is about 10% for a 4-day period orbit. The induced decrease of the star luminosity is estimated to be around 1% for a Jupiter-type planet (from the surface ratio of the disks of the two bodies). The modeling of the observed light curve provides then the physical parameters of the planet (giving the needed parameters for the parent star): orbital inclination, real mass, radius, mean density.

The prove of the giant gaseous nature of hot Jupiters was brought by the photometric observation of a transit of a planet in front of the disk of HD 209458 [7, 8] (Fig. 2.3, top right) at the time predicted by radial-velocity measurements [9, 8] (Fig. 2.3, top left). It has provided us for the first time with physical characteristics of an exoplanet, $R_{\text{pl}} = 1.4 R_{\text{Jup}}$, $M_{\text{pl}} = 0.69 M_{\text{Jup}}$, $\rho = 0.31 \text{gcm}^{-3}$, in complete agreement with theoretical predictions [43, 44]. Observations with better facilities have then drastically improved these early results (see e.g., the impressive transit luminosity curve obtained with the Hubble Space Telescope [45]).

In the same time, the transit was also observed spectroscopically with ELODIE [10] (Fig. 2.3, bottom right). In the same way as spots, the shadow on the stellar disk of a transiting planet induces deformations of the spectral lines by hiding part of the light,
coming from the approaching or receding sides of the rotating star. This effect influences the measured radial velocities in the form of an anomaly of the orbital curve (Fig. 2.3, bottom left) whose shape depends on the geometry of the transit and on stellar parameters (e.g., stellar rotation). The main results can be summarized as follow: 1) the positive sign of the anomaly curve during the ingress indicates that the stellar rotation is in the same direction as the planet motion; 2) a small angle of ~3.9° is estimated between the rotation and orbital axes; 3) the method provides an independent estimate of the stellar rotation: \( v \sin i = 3.75 \text{km s}^{-1} \).

Fig. 2.3 Transit of HD 209458 b: Top. First photometric observations on the 9th and 16th of September 1999 (right, [7]), at the phase predicted by the radial-velocity measurements (left, [9]). Bottom. Anomaly of the orbital radial-velocity curve (left) observed with ELODIE (right, [10]); JD-T\(_G\)=time difference to the center to the transit; JDB=Julian Date.
Reflected light. Hot Jupiters present a large reflecting surface to the light coming from the close star. In the visible, the reflected light represents about $10^{-5}$ of the total observed flux. Despite this very unfavorable flux ratio, the large Doppler shift of the reflected light could allow us to separate the latter from the stellar light in very high signal-to-noise spectra. This technique is even more promising in the IR where the intrinsic emission of the planet adds up to the reflected light. In the visible, the technique was intensively applied to τ Boo, but no conclusive results have been obtained yet [46].

Spectral signatures of the planet atmosphere. Because of the hot temperature, some elements of the planet atmosphere evaporate and are blown away by the high-speed solar wind. Doppler shifts of the spectral lines of those elements will then be very different for phases “off” (wind perpendicular to the line of sight) and “in” (wind in the observer direction) “transit” [47, 48]. The difficulty resides in finding the atmospheric lines which, on the other hand, provide information on the chemical composition of the planetary atmosphere.

2.5 The Mass Function of Substellar Companions

Radial velocities give only access to the minimum mass $m_2 \sin(i)$ of low-mass companions. On the long run, most of the orbital planes of known brown-dwarf and planetary companions will be determined by precise astrometric measurements (often combined with spectroscopic data) obtained either with ground-based interferometers (VLTI, KeckI) or astrometric space missions (FAME, SIM, GAIA). A significant num-
ber of orbital planes of very low-mass companions have, however, already been determined thanks to several different techniques: Hipparcos astrometric data for the heavier candidates [49, 50], transit observations [7-9] or synchronization considerations for short-period systems. For these companions we have an estimate of their real mass $m_2$. The histogram of minimum masses of companion to solar type stars, including our latest planet detections, is illustrated in Fig. 2.4 in logarithmic (left) and linear (right) scales. The top panels present the $m_2 \sin(i)$ distributions whereas the bottom diagrams show composite histograms of $m_2$ (open) or $m_2 \sin(i)$ (black, when $\sin(i)$ is not known).

Han et al. [51] have recently suggested that most of the exoplanet candidates discovered so far have masses well above the planetary limit, in the brown-dwarf or even in the stellar domain, the orbits being seen nearly pole-on. They reached this conclusion by trying to extract the astrometric orbit (hence the orbital inclination) from the Hipparcos intermediate data. As already cautioned by Halbwachs et al. [49], this approach is doomed to fail for systems with apparent separations that are below the Hipparcos sensitivity, because due to measurements errors a positive motion of the star on the sky is always observed, even for “single” stars. This is the case for most of the extrasolar planets. Moreover, the Han et al. results have been shown [52, 53] to be statistically incompatible with the hypothesis of a random distribution of orbital inclinations, expected for volume-limited samples as the CORALIE one [19].

In figure 2.4, the observed gap in the mass distribution between giant planets and stellar secondaries strongly suggests the existence of two distinct companion populations for solar type stars. The huge planetary peak is not the tail of the binary distribution. The sharp drop of the mass function observed around $8M_{\text{Jup}}$ (Fig. 2.4, right) strongly suggests a maximum mass for giant planets close to $10M_{\text{Jup}}$. In particular, the shape of the mass function does not suggest a relation between the D-burning limit ($13.6M_{\text{Jup}}$) and the maximum mass for giant planets (The discovery of free-floating brown dwarfs in $\sigma$-Orionis with masses probably below $10M_{\text{Jup}}$ [54] further refutes the D-burning limit as a good indicator of the brown dwarf-planet transition.).

Despite the huge observational bias against the detection of small-mass companions, we observe an increasing number of low-mass planets. The planetary mass function even increases towards the lower masses. In the same time, the easier-detected brown dwarfs are rare.

These conclusions completely hold when a deconvolution scheme is applied to the $m_2 \sin(i)$ distribution in order to derive a statistical planetary mass function [55].

### 2.6 Orbital Element Distributions: Traces of Planet Formation

From the observation of a very clear gap between their mass distributions, giant planets and stellar binaries are believed to have different formation mechanisms whose fossil traces should be revealed by a comparison of their orbital properties.
2.6.1 The Distribution of Periods

Due to the still strong observational bias affecting the detection of long-period planets, a significant comparison of the period distributions of planetary candidates \((m \sin(i) \leq 10 \text{ M}_{\text{Jup}})\) and spectroscopic binaries \((m \sin(i) \geq 20 \text{ M}_{\text{Jup}})\) is only possible for relatively short-period systems, for which the detection bias is vanishing. On the domain of very-short periods \((P \leq 10\text{d})\), the distribution of giant-planet periods is steeply rising for decreasing periods down to about 3 days where a cut-off is observed. The latter clearly appears in Fig. 2.5 (left) comparing the cumulative distributions of periods smaller than 10 days for giant planets and spectroscopic binaries. Several reasons related to the possible end of the migration process close to the central star may be invoked to set this limit like e.g., magnetospheric central cavity of the accretion disk, tidal interaction, Roche lobe overflow or evaporation (see above or [33]).

2.6.2 The Distribution of Eccentricities

The comparison of orbital eccentricities of spectroscopic binaries for G, K and M primaries [56-58] with the equivalent distribution for giant planets is remarkable. In Fig. 2.6 we have plotted the orbital eccentricities as a function of \(\log P\) both for double stars and giant planets. At the first glance we do not observe significant differences of orbital elements between planets and spectroscopic binaries. If the formation mechanisms for planets and double stars are different, why do we observe so similar \((e, \log P)\) distributions?

![Fig. 2.5](image_url) Cumulative distributions for planetary (solid line) and stellar companions (dashed line) to solar type stars of: periods smaller than 10 days (left) and eccentricities \((e)\) in the 40- to 300-day period range (right).
Nevertheless, some small differences may be emphasized. For planets with very short periods, most of the orbits are quasi-circular as for double stars. Planets having suffered a strong orbital migration are probably circularized by the tidal interaction with the accretion disk [29, 31]. However, we observe several quasi-circular planetary orbits with periods larger than the stellar circularization limit ($P \leq 10$ days). In this range of periods, planetary systems have smaller eccentricities than stellar binaries indicating different formations or evolutions. On another hand, a few shorter-period planets present eccentric orbits. Such configurations could be explained by the presence of an additional companion or by gravitational interaction between giant planets formed in the outer regions of the system [38, 39].

Most of the orbits of double stars with long periods are fairly eccentric. Quasi-circular long-period orbits are very rare. A similar situation exists for giant exoplanets (except for HD 27442 and HD 28185), although they are still strongly observationally biased in that period range. For periods larger than about 40 days, the comparison of double star and planet eccentricities is really surprising. With the limited-size samples presently available, we cannot see any significant distinctions between both populations. This is shown in Fig. 2.5 (right), which gives the corresponding cumulative

![Fig. 2.6](image_url)

**Fig. 2.6** Comparative $(e, \log P)$ diagram for planetary (open pentagons) and stellar companions to G+K+M solar type stars of the field (filled circles). The Earth position is indicated and starred symbols represent giant planets of the Solar System.
function of eccentricities for periods between 40 and 300 days. If the orbital eccentricity of binaries finds its origin in the disruption of small N-body systems, the generated distribution of eccentricities could be close to the distribution generated by the gravitational interactions between giant planets.

The origin of the eccentricity of extrasolar giant planets has been searched in the gravitational interaction between multiple giant planets [38, 39] or between the planets and the planetesimals in the early stages of the system formation [59]. Among the giant-planet candidates several eccentric orbits show a drift of their mean velocity, indicating the presence of a long-period companion (stellar or planetary) whose gravitational perturbation can also be suspected to be responsible for the observed (high) planetary eccentricity as e.g., for the planet orbiting 16 Cyg B [60].

In conclusion, the differences observed between planetary systems and double stars in the shape of the secondary mass functions and in the period and eccentricity distributions argue for the two populations being formed by distinct processes. More observations, however, are still needed to bring clear constraints on the possible formation and evolution scenarios.

2.7 Metal Enrichment of Stars Bearing Planets

Shortly after the discovery of the first extrasolar planets, it was pointed out that stars with planets were in average more metal rich compared to the common dwarfs of the solar neighborhood [61, 62]. With the growing number of detected candidates, this early trend is confirmed [63] and strengthened by an homogeneous metallicity determination for a set of planet-hosting and comparison stars [64] (Fig. 2.7, left). The abundance ratios of “non-Iron” chemical elements in the stellar atmosphere ([Li/H], [C/H] and [N/H]) are found to be comparable for stars with and without planets [63, 64].

The observed relation between the presence of a planet and the chemical anomaly in the stellar atmosphere is of great interest for constraining planet-formation scenarios. The main explanation for metal enrichment of stars with planets rests on the idea that an environment rich in heavy elements favors giant-planet formation. This point of view is supported by the negative result of an intensive photometric search for transiting planets in 47 Tuc [65], a metal deficient globular cluster (<[Fe/H]> = −0.7). No transit was detected whereas several dozens were expected. It should be noted however, that in the case of 47 Tuc, the absence of planet could be due to the cluster high stellar density in the monitored region. Close stellar neighbors could prevent the formation of the protoplanetary disk.

Another possible explanation relates to the hypothesis that during the period of planet formation, one or several migrating planets could fall into the central star. In such a case, the contamination should be more effective for stars with small convective zones (massive dwarf stars), what is not observed [64]. However, for HD 82943, there are spectroscopic indications of a planet engulfment by a star with two known extrasolar planets [66], suggesting that contamination could nevertheless be acting during the planet formation phase and produce stellar metal enrichment.
Normalizing the \([\text{Fe/H}]\) histogram of star hosting planets by the number of stars of the solar vicinity in given metallicity intervals, we obtain the “corrected” frequency of stars with planets per metallicity interval [64] (Fig. 2.7, right). The distribution is steeply rising for increasing metallicities and it turns out that a very large fraction of rich stars harbor giant planets. In the diagram, the Sun already resides in the “low-frequency” tail of the metallicity distribution. This could be taken as an indication that planetary systems resembling more to our own should be searched for around stars with moderate metallicity, for which the building (and perhaps the migration) of massive giant planet could be more difficult. Such systems would appear as more interesting for the search of exobiological life.

For our planet-search surveys, we take care of not introducing a bias in favor of metal-rich stars in our observational strategy, in order not to bias our interpretation of the results.

### 2.8 Summary and Future Perspectives

In about five and a half years, our understanding of planetary formation had to integrate several new peculiar characteristics brought by an increasing number of extrasolar planet discoveries. We can summarize the prominent results as follows:

- More than 5% of dwarf stars of the solar neighborhood harbor giant planets, about 1/6 of which are very close to their parent stars (hot Jupiters).
- Giant planets are detected around stars with masses ranging from 0.3 to \(1.4\ M_{\text{Sun}}\).
- The orbital characteristics of extrasolar planets are diverse. Periods range from
2.985 days to several years and the orbits can be very elongated, up to $e = 0.927$.

- From the mass distribution of substellar companions to solar type stars, the upper mass limit of extrasolar planet is estimated around $10 M_{\text{Jup}}$.
- The mass distribution of extrasolar planets increases for decreasing planet masses, despite the strong observational bias against very light companions. In particular, several planets have been detected with subsaturn minimum masses [11, 12].
- The real mass, radius and mean density have been determined for the giant planet orbiting the star HD 209458 by the observation of the photometric transit of the planet in front of the stellar disk [7-9]. Information on the geometry of the system has been obtained by the observation of the spectroscopic transit of the planet [10].
- Six multi-planet systems have been described. One is hierarchically organized ($\upsilon$ And [5, 6]), two have massive outer components (HD 168443 [14], HD 74156 [18]) and three are resonant systems (HD 83443 [13], Gl 876 [15], HD 82943 [18]).
- Giant planets are preferentially found around metal-rich stars [61-64]. No other chemical anomaly is pointed out for elements non related to Iron.
- The observed differences between the mass functions and the orbital element distributions of double stars and planetary candidates strongly suggest two different formation and evolution histories for the two populations.

What are now the expected progresses in the domain of extrasolar planet search, on short and longer time scales?

**Radial-velocity programs.** The efforts invested by the “planet-hunter” teams go in two complementary directions. On the one hand, the samples are enlarged to improve the available statistics and bring stronger constraints to the theoretical approaches of the domain. Between 2000 and 3000 stars are monitored by the different groups. They should provide several tens of additional extrasolar planet detections in the coming months/years. On the other hand, the precision is improved to get a faster access to lighter planets and multi-planet systems. The latter will probably play a preponderant role in our understanding of planetary formation. In this context, newly or soon available ESO instruments (UVES/VLT or HARPS/3.6-m [67]) open new possibilities for European astronomers.

**Astrometry.** Complementarity to the radial-velocity measurements, precise astrometric data (measure of the motion of the star on the sky due to the planet perturbation) of stars with planets will rapidly provide real masses for the known candidates. The needed precision will be achieved by interferometric techniques on large ground-based telescopes (VLTI, KeckI) or space missions (SIM, FAME). Contrarily to the radial-velocity technique mainly sensitive to short-period orbits, astrometry is more efficient for longer periods. Moreover, it will directly provide us with the real planet masses.

The complementarity between astrometric and radial-velocity measurements is illustrated in Fig. 2.8, displaying the mass of detected companions to solar type stars in function of the component separations. Precision limits of the mentioned methods are clearly indicated. The efficiency of astrometry for extrasolar planet search depends on the precision achieved for the measurements of star positions. With a precision of 10-
50 μas, the VLTI will be sensitive to most of the known planets. It should also allow the detection of a “real” Jupiter up to a distance of about 200 pc from our Sun. With an expected precision of 4 to 1 μas, SIM should be able to point out terrestrial planets around stars in our close vicinity (a few parsecs).

In addition to interferometric facilities, satellites especially designed for the precise measurements of stellar positions, parallaxes and proper motions are being studied (e.g., GAIA; see Chap. 24, Foing). Such satellites are expected to significantly contribute to the progress in the field of extrasolar planets, especially for stars non-accessible to the radial-velocity technique like TTauri, A or B stars.

Fig. 2.8 Mass-separation diagram of companions to solar type stars (planets, brown dwarfs and stellar binaries). The elongated symbols represent the $\sin i$ probability in logarithmic scale for candidates with only minimum mass determinations. Open symbols are used for low-eccentricity orbits. Solar-System planets are located by starred symbols. Finally, the precision limits of the radial-velocity technique and interferometric astrometry (VLTI: 10 and 50 μas for a star at 10 pc; and SIM: 3 μas for a star at 3 pc), are indicated by the labeled inclined shaded lines.

**Photometric transits.** Because of their simplicity and the importance of the obtained results, photometric-transit programs from the ground develop rapidly. Instru-
ments with large field of view promise to be very efficient as the expected number of detections is statistically proportional to the number of monitored stars. From the ground, the achieved photometric precision easily allows for the detection of transiting giant planets. The detection of Earth-like planets, however, is only possible from space (induced luminosity variation of about 0.01%). Several space missions aiming to detect terrestrial planets are foreseen (COROT, Eddington, Kepler). Eddington, for example, is expected to find around 2000 terrestrial planets, among them a few tens in the habitable zone of the star.

**On the long term: the search for life.** Terrestrial planets detected by space interferometric and astrometric programs or by photometric transit searches will provide ideal targets for more ambitious projects, aiming to find bio-tracers in the atmosphere of those planets. Two similar projects are being presently studied: Darwin/ESA and TPF/NASA (Terrestrial Planet Finder). They basically consist in a battery of IR telescopes in space whose light will be combined in a clever way (nulling interferometry technique) to remove the light coming from the target star and thus reveal the planetary companion. Traces of Carbon dioxide in the observed low-resolution spectra of the planet will indicate the presence of an atmosphere, that should be “habitable” if water vapor is found and even “inhabited”, at least by primitive forms of life, if Ozone is present.

So, in about 20 years, we should be able to scientifically give an answer to a fundamental philosophical question, recurrent throughout our history, on the origin, and unicity of life in the Universe. Today, the first element to the answer has already been brought by the discovery of planets around stars similar to our Sun.

### 2.9 References


