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Extra-solar planets around solar-type stars: an overview

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Abstract. Radial velocity surveys have revealed up to now about 150 extra-solar planets, among which a few multi-planetary systems. The discovered planets present a wide variety of orbital elements and masses, which are raising many problems and questions regarding the processes involved in their formation. The statistical analysis of the distributions of orbital elements, planetary masses, and relations between these, is however already giving some strong constraints on the formation of the planetary systems. Furthermore, the study of the planet host stars has revealed the crucial role of the stellar metallicity on the giant planet formation. In this paper we will review the current status of the research on this subject.

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1. Introduction

Following the discovery of a giant planet orbiting the solar-type star 51 Peg (Mayor & Queloz 1995), planet hunters have unveiled the presence of about 150 exo-worlds[1]. Globally, these discoveries, that include ∼10 multi-planetary systems (e.g. Butler et al. 1999; Mayor et al. 2004), and several confirmed transiting planets (e.g. Charbonneau et al. 2000; Konacki et al. 2003; Bouchy et al. 2004), have brought to light the existence of planets with a huge variety of characteristics, opening unexpected questions about the processes of giant planet formation. The definition of a planet has itself been put into question.

To the surprise of astronomers, planet searches have revealed giant planets with orbital periods as short as 1.2 days (Konacki et al. 2003), or as long as ∼10 years (Marcy et al. 2002), although this upper limit is probably due to observational limitations. Some of the planets are on eccentric orbits (Naef et al. 2001) more typical of some comets in the Solar System. While the most recently discovered planets have masses only one order of magnitude larger than Earth (Santos et al. 2004a; McArthur et al. 2004), some behemoths have more than 15 times the mass of Jupiter (Udry et al. 2002). It is not clear whether or not the more massive of these companions should be classified as planets at all. According to the pre-1995 planet formation theories, none of these objects were supposed to exist.

In less than 10 years, radial-velocity surveys led to the discovery of most of the known planets. Reflecting the jump in measurement precision from $\sim 5\,\mathrm{m\,s^{-1}}$ in 1995 to less than $1\,\mathrm{m\,s^{-1}}$ for the newest, state-of-the-art spectrometer HARPS (Mayor et al. 2003), the lowest known planetary mass has decreased by more than one order of magnitude.

With the numbers increasing very fast, current results are already giving us the chance to undertake the first statistical studies of the properties of the exo-planets, as well of their host stars (Cumming et al. 1999; Zucker & Mazeh 2002; Udry et al. 2003; Santos et al. 2003; Eggenberger et al. 2004; Halbwachs et al. 2005). This is bringing new interesting constraints for the models of planet formation and evolution.

Other techniques are further helping to increase the number and diversity of known exoplanets. Microlensing surveys have now detected two Jupiter-mass planetary companions around faint stars in the galactic bulge (Bond et al. 2004; Udalski et al. 2005). The degeneracy in the mod-

[1] See table at http://obswww.unige.ch/exoplanets for continuous updates; Before these discoveries, only planets around a pulsar had been detected (Wolszczan & Frail 1992). Given the violent Supernova explosion that gave origin to the pulsar, however, it is believed that these are probably second generation planets.

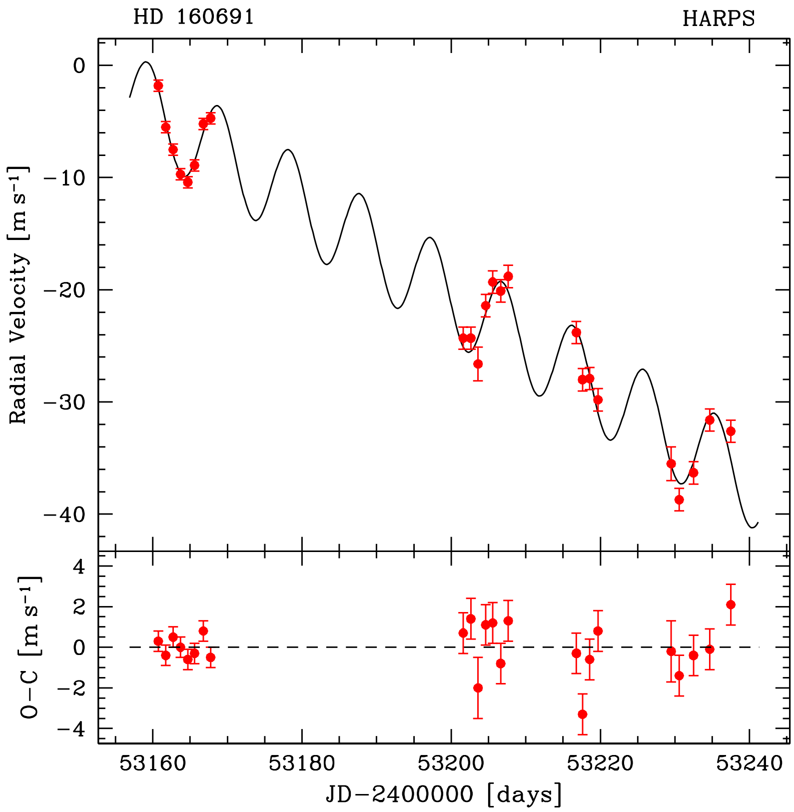

Figure 1.: *Radial-velocity measurements of μ Ara as a function of time, as obtained with the HARPS spectrograph (Mayor et al. 2003). The filled line represents the best fit to the data, obtained with the sum of a Keplerian function and a linear trend. This latter represents the effect of the long period companions to the system (one, or possibly two other giant planets are known to orbit this star). The residuals of the fit, with an rms of only 0.9* $\mathrm{m\,s^{-1}}$*, are shown in the lower panel. From Santos et al. (2004a).*

els used to explain the magnification in the observed light curves, and the non-reproducibility of these events prevent us from deriving accurate orbital parameters and masses for these planets. However, the microlensing technique remains an important tool to study the frequency of planets in the galaxy.

With somewhat more success, transit search surveys, often associated with microlensing surveys like the Optical Gravitational Lensing Experience (OGLE), have provided half a dozen of confirmed giant planets (e.g. Konacki et al. 2003; Bouchy et al. 2004) from the more than 100 announced candidates (e.g. Udalski et al. 2004). These observations are now giving the possibility to access planetary parameters like the radius, real mass, and consequently the mean density.

Finally, it may even be that the first image of an extra-solar planet has already been obtained. Using adaptative optics instruments, astronomers have now observed at least two promising candidates (Chauvin et al. 2004; Neuhäuser et al. 2005), hopefully opening the way to the discovery of many more.

In this paper we will review some of the major results on this field of research. In Sect.2. we will review the basic planet formation models. More details will be presented in the contribution of C. Terquem in this volume. We will then review some of the most important outcome of the planet search programs in Sect.3., describing the results of some statistical studies of the properties of the known exoplanets. In Sect. 4. we will then briefly mention the recent discovery of transiting planets, concluding in Sect.5., where we will discuss some future prospects. For a thorough description of the major planet-search techniques we point the reader to the papers by F. Bouchy, F. Pont and F. Malbet in this volume, and to Udry (2001).

2. A quick overview of planet formation

It is widely accepted that planets are a "simple" byproduct of the stellar formation process. In a simple view, current theory tells us that when a cloud of gas and dust contracts to give origin to a star, conservation of angular momentum leads to the formation of a flat disk of gas and dust around the central newborn "sun". During the 1980's and 1990's, evidence was gathered about the existence and frequency of such disks around young solar-type stars, both inferred from the presence of infra-red excess emission (e.g. Beckwith & Sargent 1996), or by direct imaging (e.g. McCaughrean & O'dell 1996). The existence of these proto-planetary disks is currently beyond doubt.

Planets are then though to be formed in these disks by the gathering of material. This model, that was quantitatively developed in the works of V. Safranov in the 1960's, theorizes that as time passes, and by a process that is still not completely understood (see e.g. Wurm et al. 2001), dust particles and ice grains in the disk are gathered to form the first planetary seeds. In the inner part of the disk, where temperatures are too high and volatiles cannot condensate, silicate particles are gathered to form the telluric planets like our Earth.

In the "outer" regions of the disk, where ices can condensate, these "planetesimals" are thought to grow in a few million years. When such a "planetesimal" achieves enough mass (about 10 times the mass of the

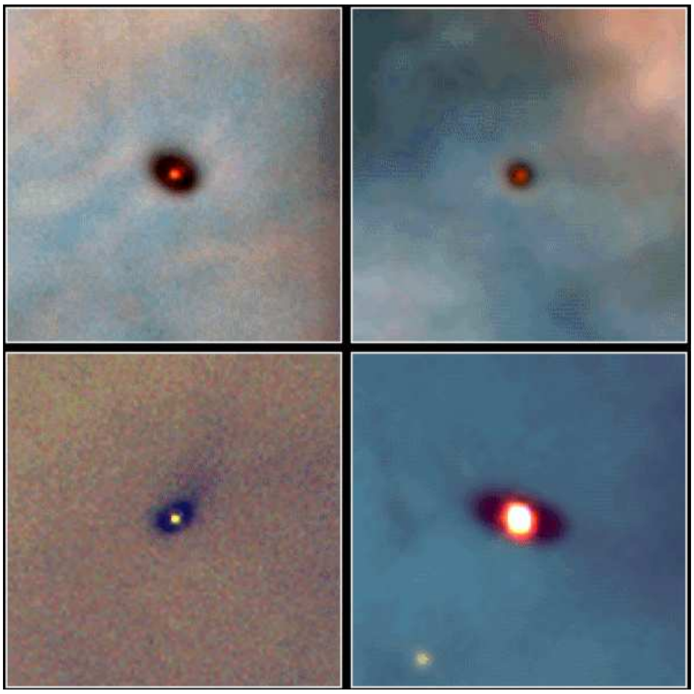

Figure 2.: *Disks in the Orion nebula observed by the Hubble Space Telescope (McCaughrean & O'dell 1996). Courtesy of M.J. McCaughrean, C.E. O'Dell and NASA.*

Earth), its gravitational pull enables it to accrete gas in a runaway process that gives origin to a giant gaseous planet similar to the outer planets in our own Solar System (e.g. Perri & Cameron 1974; Mizuno 1980; Pollack et al. 1996). This giant planet formation scenario is usually dubbed the core accretion model. In this model, a solid core is first formed by the accretion of planetesimals. As the core grows, it eventually becomes massive enough to gravitationally bind some of the nebular gas thus surrounding itself by an envelope. The evolution of this core-envelope has been studied in detail by Pollack et al. (1996) and it was shown that the solid core and the gaseous envelope grow in mass, the envelope remaining in quasi-static and thermal equilibrium. During this phase, the energy radiated by the gas is supplied by energy released from the accretion of planetesimals. As the core mass reaches a critical value (of the order of $15\,M_\oplus$ at 5 AU, but depending on different physical parameters, such as the solid accretion rate onto the core), radiative losses can no longer be offset by planetesimal accretion and the envelope starts to contract. This increases the gas accretion rate which in turn raises the radiative energy losses causing the process to run away leading to the very rapid build up of a massive envelope.

This model thus needs the growth of a critical core before the disappearance of the disk. However, this point is not granted. The lifetime of proto-planetary disks can be estimated from astronomical observations by relating the total mass of the disks (Beckwith & Sargent 1996) to the mass accretion rate (Hartmann et al. 1998). This yields a lifetime for these objects of 1-10 My, in agreement with the frequency of disks in open clusters of different ages (Haisch et al. 2001). Because this lifetime is of the same order, if not smaller, than the planet formation time-scale, a fast growth of the core is essential.

There are two ways of solving this problem. Either we suppose that cores can grow faster, or disk life-times are longer than currently believed. Fast growth is thought to occur preferentially beyond the so-called ice line, the point where the nebula becomes cold enough for ices to condensate (Lodders 2003) thereby maximizing the density of solids available for accretion. In solar nebula models, this was thought to occur around or beyond roughly 3 AU and therefore explained the dichotomy between the inner (rocky) and outer (icy-gaseous) planets in the solar system. However, it has recently been shown that if growing cores are allowed to migrate (Alibert et al. 2004), or if random migration occurs in a turbulent disk (Rice & Armitage 2003; Nelson & Papaloizou 2004) they accrete much faster and therefore giant planets can form well within inferred disk lifetimes. Finally, it may even be that gas disks last longer than previously though (Bary et al. 2003). Disk life-times may thus not be a problem after all.

An alternative solution to speed-up the giant planet formation is to adopt another planet-formation model. Boss (1997) has proposed that giant planets can form directly from the gravitational fragmentation and collapse of a proto-planetary disk (Boss 1997; Mayer et al. 2002). Owing to the numerical difficulties involved in following this process, there are, however, still a number of open issues. For example, the formation and survival of bound structures is still being debated because most calculations so far have used an isothermal equation of state and/or inadequate resolution. Furthermore, the bound structures formed are always significantly more massive than Jupiter, therefore it is not yet clear whether smaller mass giant planets (a Saturn for example) can be formed by this mechanism (see however, Boss et al. 2002). Finally, it remains to be seen if such a formation mechanism can account for the peculiar composition and structure (enrichment in heavy elements compared to solar and size of solid core) of Jupiter and Saturn (e.g. Owen 2003).

3. Statistical properties of exoplanets

The huge diversity of extra-solar planets brought new and important problems to the theories of planet formation and evolution. How and where are giant planets formed? Why do we find such a diversity? These questions still lack a clear answer, but current data is already providing us with strong constraints to improve the theories of planet formation and evolution.

3.1 The Mass distribution

One important clue concerning the nature of the now discovered planetary systems comes from their mass distribution (Fig. 3).

Several conclusions may be taken from the plots. First, a look at the upper panel of Fig. 3, shows that there is a clear gap in the mass distribution of the companions to solar-type stars. This gap, separating low mass stellar companions from the planetary-mass objects (often called the "brown dwarf desert") represents a strong evidence that these two populations are the result of different formation and/or evolution processes.

A zoom-up of the low-mass part of this plot (lower panel of Fig. 3) also tells us something very interesting. We can see here that although the radial-velocity technique is more sensitive to more massive companions, the planetary mass distribution rises towards the low mass regime. Furthermore, the distribution drops to zero at masses around $\sim$10 M_{Jup} (Jorissen et al. 2001), although the tail of the distribution may extend up to a mass of $\sim$20 M_{Jup}. This limit is not related to the Deuterium-burning mass limit of $\sim$13 M_{Jup} (Saumon et al. 1996), sometimes considered as the arbitrary limiting mass for a planet[2]. As it was recently shown by Jorissen et al. (2001), this result is not an artifact of the fact that for most of the targets we only have minimum masses, but a real upper limit for the mass of the planetary companions discovered so far, since it is clearly visible in a deconvolved distribution, where the effect of the unknown orbital inclination was taken into account.

3.2 Orbital Period

One of the most interesting problems that appeared after the first planets were discovered has to do with the proximity to their host stars. In contrast with the current observations, giant planets were previously thought to form (and be present) only at distances of a few A.U. from

[2]This value is an arbitrary limit used as a "working definition", but it is not related to the planetary formation physics

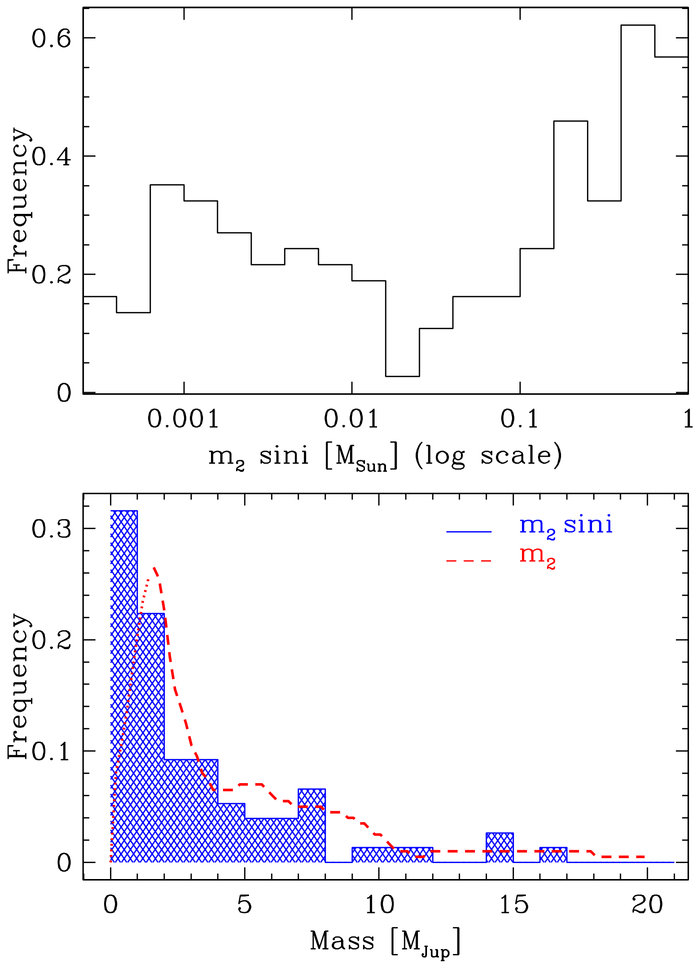

Figure 3.: *Mass function of companions to solar-type stars in log (top) and linear (bottom) scales. In the lower panel, the dashed line represents the result of a statistical deconvolution of the observed distribution in order to take into account the effect of the orbital inclination. As in Jorissen et al. (2001).*

their "suns" (Pollack et al. 1996). However, and in striking contrast with the predictions, the first exoplanets were found very close to their parent stars. This result has led to a change in the paradigm of planetary formation and evolution. To explain the new systems, it is now clear that the theories have to include orbital migration.

Migration can be due to several physical processes such as gravitational scattering in multiple systems (Marzari & Weidenschilling 2002) as

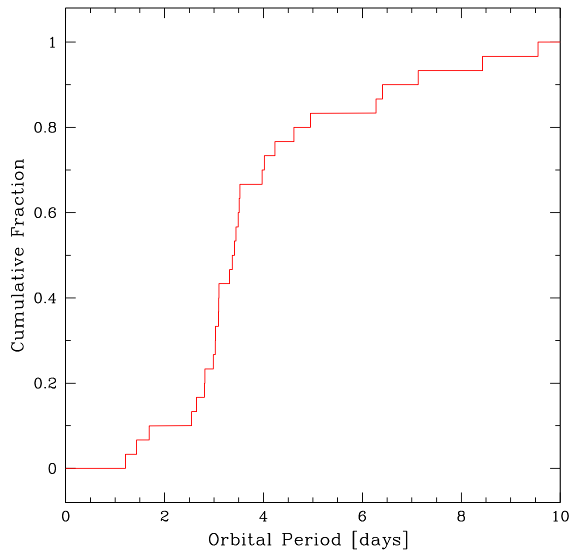

Figure 4.: *Cumulative function of orbital periods for short period (<10 day) exoplanets. Note the sharp slope of this function for periods near 3-days.*

well as gravitational interactions between the gaseous and/or the planetesimal disk and the planet (Lin et al. 1996; Murray et al. 1998). Note that these two mechanisms must necessarily occur and interactions between an embedded planet and a gaseous disk had been discussed before the discovery of the first exoplanet (Goldreich & Tremaine 1980). The question is therefore not whether migration takes place or not but rather what its direction and amplitude is.

Two major types of migration modes have been identified depending on whether the planet is massive enough to open a gap in the disk (type II migration) or not (type I migration) (Lin & Papaloizou 1986; Lin et al. 1996; Ward 1997; Tanaka et al. 2002). All these models conclude that planets are migrating mostly inward. Furthermore, migration timescales obtained so far are so short (especially for type I migration) that, in almost all cases, planets should not survive but fall into their host star (see e.g. Trilling et al. 1998; Alibert et al. 2004). Because planets are actually observed, in large numbers, and at various distances to their stars, we must conclude that our migration theory is incomplete. New ideas for slowing down migration at least for lower mass planets based on MHD turbulence have been proposed recently (Nelson & Papaloizou 2004).

Although still quite biased for the long period systems (more difficult to detect by the radial-velocity surveys), the period distribution of the extra-solar planetary companions can already tell us something about the planetary formation and evolution processes. This is particularly true for the short period systems, for which the biases are not so important. In particular, one of the most impressive features present in the current data is the clear pile-up of planetary companions with periods ∼3 days (see Fig. 4), while for smaller orbital periods only a few cases exist (see review by Gaudi et al. 2004).

This result is in complete contrast with the period distribution for stellar companions. Stellar binaries are not limited to periods longer than this limit, even when the mass of the secondary is in the brown-dwarf domain (see e.g. Santos et al. 2002b; Mayor & Santos 2003). This observation thus means that somehow the process involved in the planetary migration makes the planet preferentially "stop" at a distance corresponding to this orbital period. The physical mechanism responsible for halting and parking the planet at short distances from the host star is still being debated. Possible mechanisms include the existence of a central cavity in the disk, tidal interaction with a fast spinning host star or even Roche lobe overflow (Trilling et al. 1998). Another possibility is that planets venturing closer are photo-evaporated by the radiation field emitted by the host star thus becoming too small to be detected or vanishing altogether (Vidal-Madjar et al. 2003; Baraffe et al. 2004). The case of the few new OGLE transiting planets (Konacki et al. 2003; Bouchy et al. 2004) having orbital periods of less than 2-days, may in this context be interpreted as the tail of the short period planets distribution (Gaudi et al. 2004).

3.3 The Mass-Period relation

A lot of constraints for the migration scenarios are now being put forward by the analysis of the mass-period relation. Recent results have shown that there seems to be a strong relation between the mass and orbital period of the giant planets. Indeed, a look at Fig. 5 (where we plot these two quantities) reveals a paucity of high-mass planetary companions ($M > 2\,M_{Jup}$) orbiting in short period (lower than ∼100-days) trajectories (Zucker & Mazeh 2002; Udry et al. 2003). This trend, clearly significant[3], is less evident for those planets orbiting stars that have other stellar companions, showing that planet formation (and/or evolution) might be influenced in these systems (Eggenberger et al. 2004). But overall, these results are indeed compatible with the current ideas about

[3]These planets are the easiest to find using radial-velocity instruments

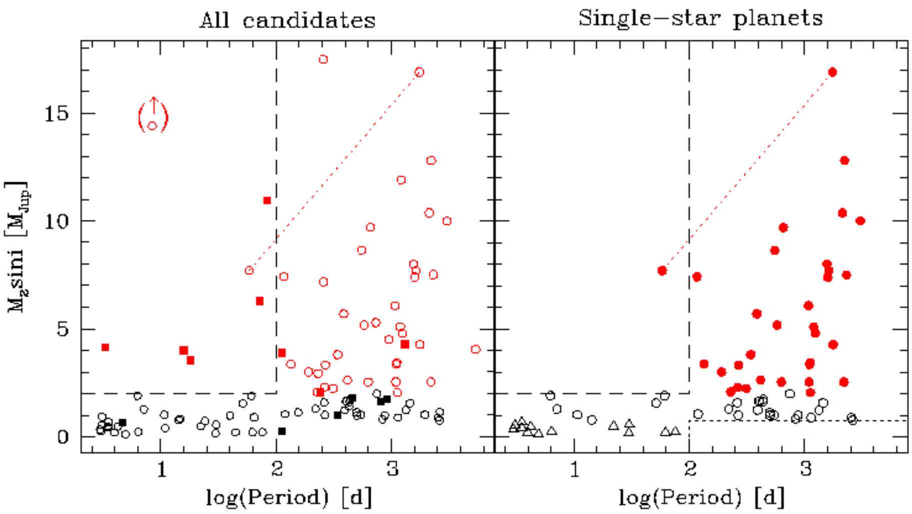

Figure 5.: *Minimum masses versus periods for known exoplanet candidates. In the left panel, filled squares indicate planets in binaries whereas circles are used for planets around single stars. In the right panel, only planets orbiting single dwarf stars are represented. A different coding is used for massive ($m_2 \sin i \geq 2\,M_{\rm Jup}$; filled symbols), intermediate-mass ($m_2 \sin i$ between 0.75 and $2\,M_{\rm Jup}$; open circles), and lighter ($m_2 \sin i \leq 0.75\,M_{\rm Jup}$; open triangles) candidates. The dashed and dotted lines in the panels indicate limits at $P = 100$ d (vertical), at $m_2 \sin i = 2\,M_{\rm Jup}$ (horizontal left), or at $m_2 \sin i = 0.75\,M_{\rm Jup}$ (horizontal right). See Udry et al. (2003a) for more details.*

planetary orbital migration (either due to an interaction with the disk or with other companions) – (e.g. Trilling et al. 2002) – that teach us that the higher mass planets should migrate less.

Curiously, on the other side of the distribution, there also seems to be a paucity of very low mass giant planets orbiting in long period orbits (Udry et al. 2003) – Fig. 6. Actually, all planets with mass lower than about 0.75 $_{Jup}$ are found at close distances from their stars. And although such a trend could be expected from biases related to the radial-velocity surveys, Monte-Carlo simulations have shown that this result is indeed statistically significant. Furthermore, it seems that from the theoretical point of view, this observations might be explained in a scenario of run-away migration, a phenomenon that seems to be very dependent on the mass of the planet (Masset & Papaloizou 2003).

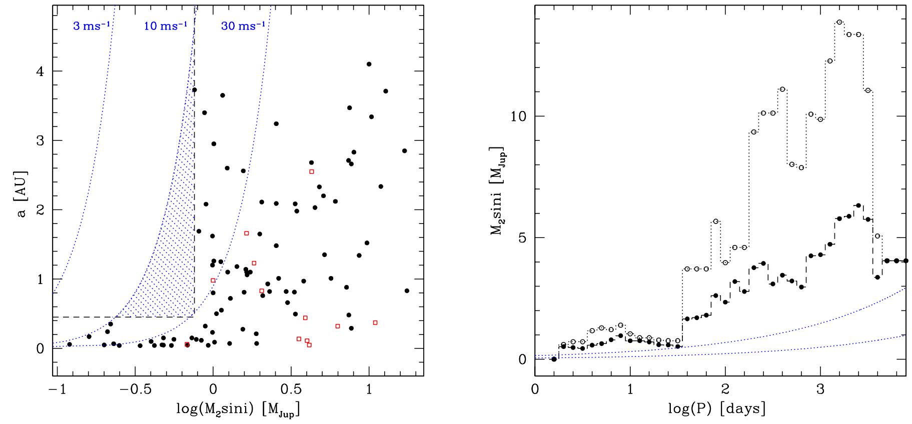

Figure 6.: *Left panel: Mass-separation diagram for the known exoplanet candidates. The dotted lines illustrate the radial-velocity semi-amplitude expected on a solar-mass star due to planets on circular orbits with given minimum masses and separations. The shaded area empty of planets is shown not to be due to small number statistics. Planets in binaries are indicated by open symbols. Right panel: Mean mass (filled circles), or higher mass (average on the 3 higher values; open circles) of planets in period smoothing windows with* $\log P = 0.2$. *From Udry et al. (2003a)*

In other words, low mass planets seem to migrate very fast, while their high-mass counterparts do not migrate significantly from their initial positions. The higher the mass of a planet, the less it will migrate (see also right panel of Fig. 6). One of the consequences of this is the low number of planets at intermediate periods (Udry et al. 2003), forming the now called period-valley. It should be noted, however, that this "rule" apparently cannot be extrapolated to e.g. much lower mass planets or planets formed at very large distances from the star (e.g. Uranus and Neptune).

Together with these findings, it has recently been suggested that there might be a relation between mass ratio and period ratio for planets in multiple systems (Mazeh et al. 2004). If confirmed, this trend may also be telling us something more about the formation and evolution of multi-planetary systems.

3.4 The orbital eccentricity

One of the most enigmatic results to date is well illustrated in Fig.7. A first look at the figure 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,

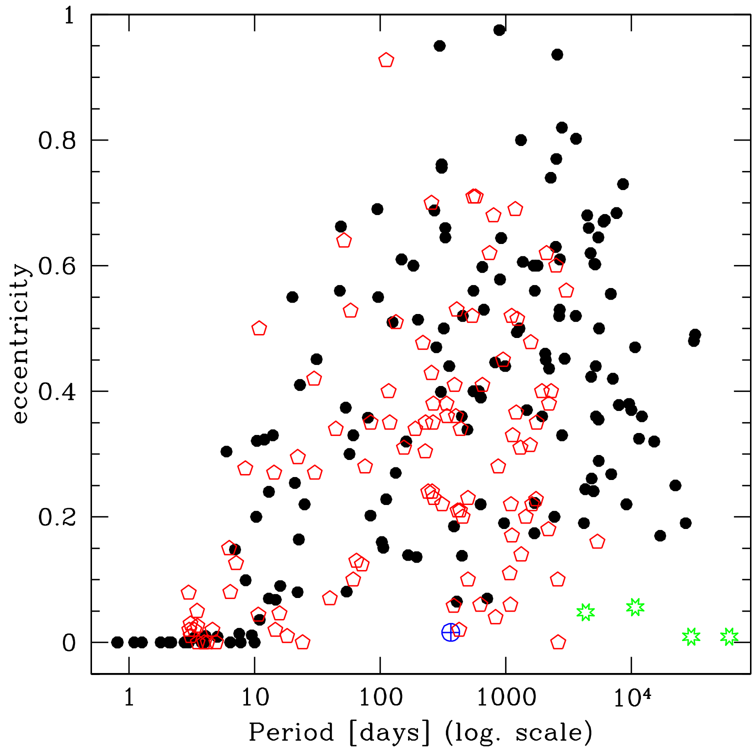

Figure 7.: *The e − log P diagram for planetary (open pentagons) and stellar companions (filled circles) to solar type field dwarfs. Starred symbols represent the giant planets of our Solar System, while the "earth" symbol represents our planet.*

have basically the same distribution in this plot? And how then can this be fit into the "traditional" picture of a planet forming in a disk?

We should note that the absence of short period binary systems with high eccentricity is well explained by tidal circularization effects (see e.g. Mayor & Mermilliod 1984; Zahn 1989; Tassoul 2000, and references therein).

Although not clear from Fig.7, there seems indeed to exist a significant difference between the eccentricities of the stellar and planetary companions (Halbwachs et al. 2005). These differences again suggest that some different mechanisms acted in the formation of planets.

In any case, we will need to explain how the two distributions are so similar, and why planets may achieve such high eccentricities. For masses lower than $\sim 20\,M_{Jup}$, it has been suggested that the interaction (and migration) of a companion within a gas disk may have the effect of damping its eccentricity (Goldreich & Tremaine 1980; Ward 1997). This implies that other processes may play an important role in defining the "final" orbital configuration. Possible candidates include the interaction between planets in a multiple system (Rasio & Ford 1996; Chiang et al. 2002), between the planet and a disk of planetesimals (Murray et al. 1998), the simultaneous migration of various planets in a disk (Murray et al. 2002), the influence of a distant stellar companion (Kozai 1962; Holman et al. 1997; Takeda & Rasio 2005) or by encounters with stars passing (Zakamska & Tremaine 2004). Other proposed mechanisms involve the interaction with the gaseous disk itself (Goldreich & Sari 2003) or the influence of star-disk winds or stellar jets (Namouni 2005). In this respect, one particularly interesting case of very high eccentricity (above 0.9) amongst the planetary companions is the planet around HD 80606 (Naef et al. 2001).

3.5 The metal-rich nature of planet host stars

Up to now we have been reviewing the results and conclusions we have obtained directly from the study of the orbital properties and masses of the discovered planets. But another particular fact that is helping us to understand the mechanisms of planetary formation has to do with the planet host stars themselves. In fact, they were found to be particularly metal-rich, i.e. they have, in average, a metal content higher than the one found in stars without detected planetary companions (Gonzalez 1998; Gonzalez et al. 2001; Santos et al. 2001, 2003, 2004c, 2005; Reid 2002). This result, clearly confirmed by an uniform spectroscopic analysis of large samples of stars with and without detected giant planets (Santos et al. 2001), was further shown not to be due to any sampling or observational biases (Santos et al. 2003), and is obtained by using different kinds of techniques to derive the stellar metallicity (e.g. Giménez 2000; Reid 2002). Furthermore, this excess seems to be real for all the metals studied up to now (e.g. Santos et al. 2000; Gonzalez & Laws 2000; Gonzalez et al. 2001; Smith et al. 2001; Takeda et al. 2001; Sadakane et al. 2002; Bodaghee et al. 2003; Ecuvillon et al. 2004a,b; Beirão et al. 2005).

Although still not completely proved (e.g. Vauclair 2004), the most recent studies seem to favor that this metallicity "excess" is original from the cloud that gave origin to the star/planetary system (Pinsonneault et al. 2001; Santos et al. 2001, 2003; Sadakane et al. 2002) and not a result of the engulfment of planetary (iron rich) material into the stellar convective envelopes. There are, however, some hints of stellar pollution (Israelian et al. 2001, 2003; Laws & Gonzalez 2001), but not necessarily capable of changing significantly the global metal-content of the star. The lack of significant stellar pollution is corroborated by a few studies of the

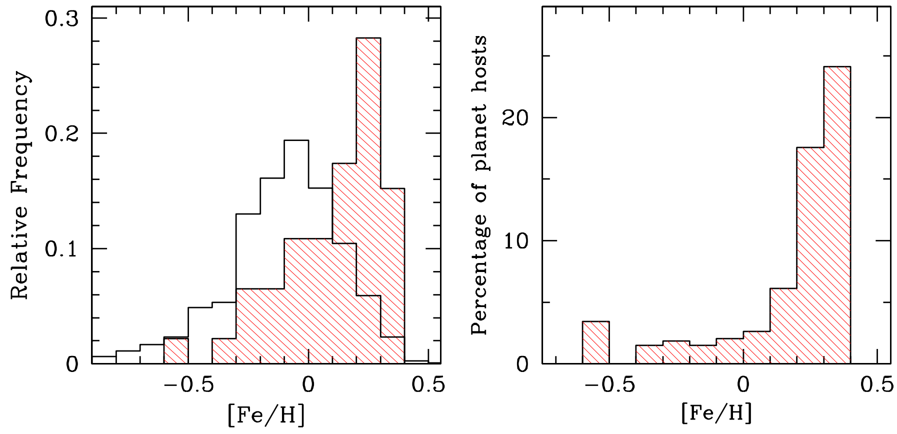

Figure 8.: *Left: metallicity distribution of stars with planets making part of the CORALIE planet search sample (shaded histogram) compared with the same distribution for the about 1000 non binary stars in the CORALIE volume-limited sample. Right: the result of correcting the planet hosts distribution to take into account the sampling effects. The vertical axis represents the percentage of planet hosts with respect to the total CORALIE sample. As in Santos et al. (2004c).*

light element abundances of stars with giant planets (e.g. Garcia Lopez & Perez de Taoro 1998; Gonzalez & Laws 2000; Ryan 2000; Deliyannis et al. 2000; Israelian et al. 2003, 2004; Santos et al. 2002a, 2004b).

Furthermore, and most importantly, the results show that the probability of finding a planet is proportional to the metallicity of the star: more metal-rich stars have a higher probability of harboring a planet than lower metallicity objects (Santos et al. 2001, 2003, 2004c; Reid 2002; Laws et al. 2003) – Fig.8, right panel. About 3% of solar-metallicity stars seem to harbor a planetary-mass companion, while more than 20% of stars with twice the solar metallicity have detected orbiting planets. This observation can even be reproduced by current theoretical models (Ida & Lin 2004; Kornet et al. 2005).

A possible and likely interpretation of this is saying that the higher the metallicity of the cloud that gives origin to the star/planetary system (and thus the dust content of the disk), the faster a planetesimal can grow, and the higher the probability that a giant planet is formed before the proto-planetary disk dissipates. In other words, the metallicity seems to be playing a key role in the formation of the currently discovered extra-solar planetary systems (see e.g. discussion in Santos et al. 2004c, for further details).

These conclusions have many implications for the theories of planetary formation. In this respect, two main cases are now debated in the literature. On the one side, the traditional core accretion scenario (Pollack et al. 1996) tells us that giant planets are formed as the result of a runaway accretion of gas around a previously formed icy core with about 10 times the mass of the Earth. As mentioned in Sect.2., and opposite to this idea, Boss (1997) has proposed that giant planets may form by a disk instability process. However, according to the instability model, the efficiency of planetary formation should not be dependent on the metallicity of the star/disk (Boss 2002). The results presented above, showing that the probability of finding a planet is a strong function of the stellar metallicity, thus favor the former (core-accretion) model as the main mechanisms responsible for the formation of giant planets (although they do not completely exclude the disk instability model).

It should be cautioned, however, that it is not known precisely how the influence of the metallicity is influencing the planetary formation and/or evolution; for example, the mass of the disks themselves, that can be crucial to determine the efficiency of planetary formation, is not known observationally with enough precision. Furthermore, the effect of the opacity and grain density may play important and not completely understood effects (Hubickyj et al. 2005).

4. Transiting planets: probing the planet structure

Up to now we have almost exclusively discussed the properties of planets discovered by the radial-velocity method. However, this gives us information only about the orbital parameters of the planets and their minimum masses, but nothing about their physical properties such as radius or mean density. Fortunately, the recent detection of seven cases (Charbonneau et al. 2000; Konacki et al. 2003; Bouchy et al. 2004; Pont et al. 2004; Alonso et al. 2004; Bouchy et al. 2005; Konacki et al. 2005) of photometric transits has provided us with the additional information to derive these quantities.

These discoveries have also raised further interesting and troubling issues. For example, among the 7 confirmed transiting planets, HD 209458 has a mean density much smaller than the other ones. Furthermore, the planets with shorter orbital periods are also the most massive ones, indicating that there might be a relation between planet mass and orbital period (Mazeh et al. 2004).

Further to the internal structure, the detection of transiting planets opens a new possibility to study the planetary atmospheres. When the planet crosses the stellar disk, its upper atmosphere acts as a filter, absorbing the light coming from the star at some preferential wavelengths that correspond to atomic/molecular transitions occurring in its atmosphere. Due to this effect sodium absorption features were detected in the atmosphere of the planet orbiting HD 209458 (Charbonneau et al. 2002). Further observations have also recently suggested that this giant planet is evaporating, as carbon and oxygen atoms are blown away along with its hydrodynamically escaping hydrogen atmosphere (Vidal-Madjar et al. 2004). Finally, in two cases it was possible to directly measure the infra-red flux of the planet (Charbonneau et al. 2005; Deming et al. 2005), permitting to derive the temperature for these bodies.

These results are presented in more detail in the contribution by F. Pont in this volume.

5. Concluding remarks and prospects for the future

The study of extra-solar planetary systems is giving its first steps. After only 10 years, we can say that at least 5% of the solar type dwarfs have giant planetary companions, with masses as low as a few earth masses and orbital separations up to a few AU (the limits imposed by the current planetary search techniques).

As we have seen above, the observed correlations between the orbital parameters of the newly found planets are giving astronomers a completely different view on the processes of formation and evolution of the planetary systems. As the numbers increase, the first statistically significant studies (e.g. Udry et al. 2003; Eggenberger et al. 2004; Halbwachs et al. 2005) give us the opportunity to revise the theories. Slowly we are building a new picture.

Furthermore, the analysis of the chemical properties of the planet host stars is giving us a lot of interesting information (e.g. Santos et al. 2004c). These latter studies have revealed the crucial role the metallicity is playing into the formation of the currently found planetary systems, showing that the percentage of stars harboring giant planets is a strongly rising function of the stellar metallicity.

As the planet search programs continue their way, many more planetary companions are expected to be discovered in the next few years. In particular, many hopes are now coming from state-of-the-art spectrographs like HARPS (Mayor et al. 2003), capable of achieving the 1m/s precision. This will give us the opportunity to improve the statistical analysis, and to better understand the physics beyond the formation of the planetary systems. While the detection of an Earth-like planet is probably beyond the reach of current techniques, the discovery in August 2004 of two planets (Santos et al. 2004a; McArthur et al. 2004) with a minimum mass of about $14\,M_{\oplus}$ orbiting sun-like stars (μ Ara c and 55 Cnc e, Fig. 1), as well of a slightly more massive exoplanet (with

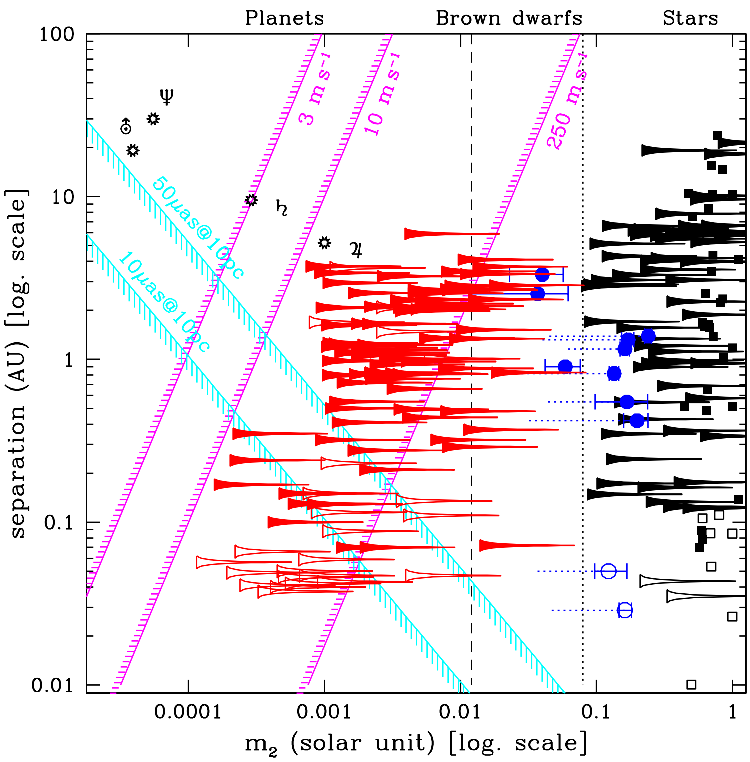

Figure 9.: *Mass against orbital separation for planets and stellar to solar type stars. The solar-system giant planets are also shown. Different lines represent the limits of detection with radial-velocity with precisions of 3, 10, and 250 m/s, and with astronomy precision of 50 and 10 μarcsec (for a star at 10pc).*

a minimum mass of 21 $M_\oplus$) orbiting the M-dwarf GJ 436 (Butler et al. 2004) implies that we are only a factor of ten in mass away from this goal. The nature of these planets is still under debate (Santos et al. 2004a; Ida & Lin 2005; Baraffe et al. 2005), but they may well be rocky.

From the *astrometric* point of view, the expectations are also very high. Instruments like the VLTI or KeckI will give us the possibility to estimate real masses for many of the known planetary systems (see Fig. 9). Furthermore, space missions like GAIA or the interferometric mission SIM, capable of achieving the few micro-arcsecond precision, will completely change the current landscape by adding tens of thousands of new planets. Given that astrometry is more sensitive to longer period systems (contrary to the radial-velocity method), these projects will also permit to better cover the period distribution of the exo-planets. It will further permit to find planets around targets not accessible with radial-velocity surveys, like A or B stars, or T Tauri stars.

Further hopes will come from *photometric transit* searches, mostly based upon space missions like COROT or Kepler. Out of the Earth's atmosphere, these satellites will achieve a photometric precision better than 0.01%, permitting the detection of transiting earths. Such detections will give the possibility to study the structure of the exoplanets and low mass stellar companions (e.g. Pont et al. 2005), and put new constraints into the theories of planet formation (see also contribution by F. Pont on this volume).

Finally, the recent discovery of two possible giant planets by direct imaging (Chauvin et al. 2004; Neuhäuser et al. 2005) has opened the way for the discovery of many more such systems.

Once earth-like planets orbiting in the habitable zone are known, the search for life in these systems will undoubtedly follow. The question of its existence is too important to be ignored even if the technology required and the cost involved are currently still staggering. Hence, future space missions will have to be launched that are capable to remotely sense the presence of life. The space interferometers Darwin (ESA) or TPF (NASA) are precisely such missions. Using, for instance, nulling interferometry techniques (to remove the light from the target stars, leaving only the photons coming from the planet), the spectroscopic signatures of life could be detected in the atmospheres of these planets. The once ideal search for life outside the solar system may soon become a reality.

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