Extra-Solar Planets

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Introduction

The widely accepted picture of stellar formation tells us that a planetary system is a simple by-product of the stellar formation process. When a cloud of gas and dust contracts to form a star, conservation of angular momentum induces the formation of a flat disk around the central newborn "sun". By a process still not fully understood, this disk is believed to be the stage for the planetary formation. According to the traditional paradigm, dust particles and ice grains in the disk are gathered to form the first planetary seeds (e.g. Pollack et al. 1996). 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 Earth), its gravitational pull is sufficiently strong for it to start accreting gas in a runaway process that gives origin to a giant gaseous planet similar to the outer planets in our own Solar System. Later on, in the inner part of the disk, where temperatures are too high and volatiles cannot condensate, silicate particles are gathered to form the telluric planets like our Earth.

In the past decade, images taken by the NASA/ESA Hubble Space Telescope (HST) have revealed a multitude of such proto-planetary disks in the Orion stellar nursery, showing that disks are indeed very common around young solar-type stars. This supports the idea that extra-solar planets should be common. However, such systems have escaped detection until very recently.

In fact, it was not until 1995, following the discovery of the planet orbiting the solar-type star 51Peg May95, that the search for extra-solar planets had its first success[1]. This long wait was mainly due to the difficulty of detecting such bodies. Planets are cold objects, and their visible spectrum results basically from reflected light of the parent star. As a result, the planet/stellar luminosity ratio is of the order of 10^{-9}. Seen from a distance of a few parsec, a planet is no more than a small "undetectable" speckle embedded in the diffraction and/or aberration of the stellar image.

The detection of exoplanets has thus been based, up to now, upon "indirect" methods. In particular, all the planetary discoveries were only possible due to the development of high-precision radial-velocity techniques. These methods, that measure the motion of a star along the line of sight (by measuring the Doppler shift of spectral lines), have now achieved precisions of the order of a few m s^{-1} ($\Delta\lambda/\lambda \sim 10^{-8}$). Such a high precision is indeed needed to find a planet: for example, Jupiter induces a periodic perturbation with an amplitude of only 13 m s^{-1} on the Sun!

In this article we will review the current status of planetary searches, presenting the major challenges that we are facing at this moment. We will then discuss how new and future generation instruments and missions will help to answer the most important questions. We will concentrate mostly on the results we can expect from future radial-velocity campaigns with state-of-the-art instruments like HARPS on the ESO 3.6-m telescope (see article by Pepe et al. in this issue).

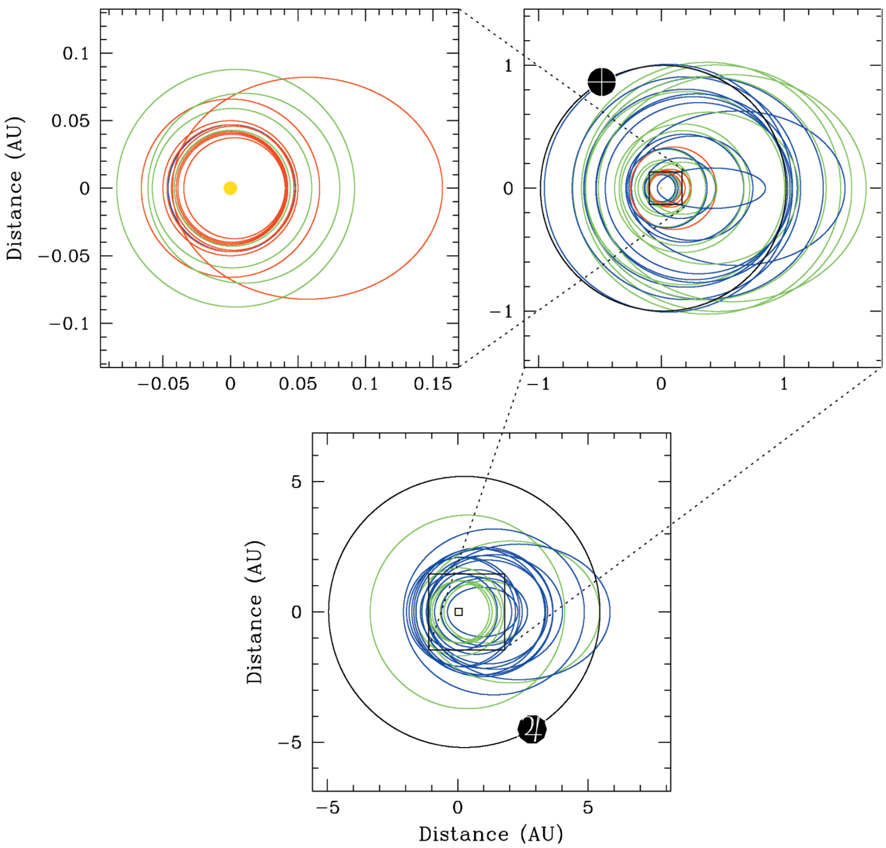


Figure 1: Schematic orbital configurations for some of the newly found extra-solar planets in three different scales. In the upper-left panel we represent the orbits of the shorter-period companions. The Sun (yellow circle) is drawn to scale. This plot illustrates well both the proximity of these planets to their host stars, and the complete lack of planetary companions orbiting closer than a certain distance (see text for more details). The upper-right and lower panels illustrate the situation concerning longer orbital period planets. In these two plots, the orbits of the Earth and Jupiter are also drawn for comparison (with the usual symbols). These three panels clearly illustrate the huge variety of orbital parameters presented by the extra-solar planets.

A Diversity of Planets

Today, about 100 extra-solar planetary systems have been unveiled

[1]Before this discovery, only planets around a pulsar had been detected (Wolszczan & Frail 1992); however, these are probably second-generation planets. In this article we will concentrate on planets around solar-type stars.

around stars other than our Sun[2]. These discoveries, which include ~ 10 multi-planetary systems, have brought to light the existence of planets with a huge variety of characteristics, opening unexpected questions about the processes of giant planetary formation.

The diversity of the discovered extra-solar planets is well illustrated in Figure 1. Unexpectedly, they don't have much in common with the giant planets in our own Solar System. Contrarily to these latter, the "new" worlds present an enormous and unexpected variety of masses and orbital parameters (astronomers were basically expecting to find "Jupiters" orbiting at ~5 A.U. or more from their host stars in quasi-circular trajectories). The majority of the discovered planets were not even supposed to exist according to the traditional paradigm of giant planetary formation (e.g. Pollack et al. 1996). Their masses vary from sub-Saturn to several times the mass of Jupiter. Some have orbits with semi-major axes smaller than the distance from Mercury to the Sun, and except for the closest companions, they generally follow eccentric trajectories, contrarily to the case of the giant-planets in the Solar System.

These findings have put into question the former planetary formation paradigm. However, the relatively large number of discovered planets is already permitting us to undertake the first statistical studies of the properties of the exoplanets, as well as of their host stars. This is bringing new constraints to the models of planet formation and evolution. Let us then see in more detail what kind of problems and information these new discoveries have brought.

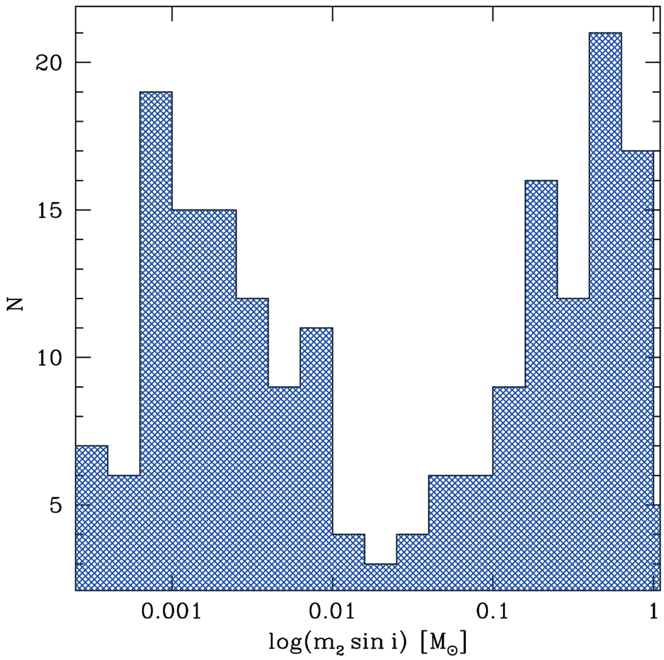


Figure 2: Distribution of minimum masses for the currently discovered low-mass companions to solar-type stars. Although the radial-velocity method has a higher sensitivity to higher-mass companions, the observed distribution rises very steeply towards the low-mass domain. From this mass up to the stellar regime, only a few objects were detected; this region is usually denominated the "Brown-Dwarf desert". This gap in the mass distribution of low-mass companions to solar-type stars supports the view that the physical mechanisms involved in the formation of these two populations (planets vs. stars) are very different.

The Period Distribution

One of the most interesting problems that appeared after the first planets were discovered has to do with the proximity to their host stars. The first planet discovered (around 51Peg – Mayor & Queloz 1995) is exactly the first such example: it orbits its star once every 4.2 days, corresponding to an orbital radius of only 0.05 A.U. This is much less than the distance from Mercury to the Sun.

The problem that was raised with the finding of these 51Peg-like planets (usually called "hot-Jupiters") resides in the fact that at such close distances the temperatures are too high for ices to condensate, and there does not seem to exist enough available material to form a Jupiter-mass planet. It is thus very difficult to imagine that such worlds could be formed so close to the central stellar furnace.

In order to explain the newly found systems, several mechanisms have thus been proposed. Current results show that *in situ* formation is very unlikely, and we need to invoke inward migration, either due to gravitational interaction with the disk (Goldreich & Tremaine 1980) or with other companions to explain the observed orbital periods. In other words, the observed close-in planets could simply have been formed far from their host star, and then migrated inwards.

But the migration mechanisms, that have broken long-lasting ideas of "stability" of the planetary systems, have some problems to solve. According to the models, the timescales of planetary migration in a disk are particularly short. This means that more than worrying about how planets migrate after or during their formation, we need to understand how migration can be stopped (and/or slowed down)!

One particularly interesting clue comes from the observation that there is a clear pile-up of planetary companions with periods around 3 days, accompanied by a complete absence of any system with a period shorter than this value. This result, which is in complete contrast with the period distribution for stellar companions (we can find double stars with periods much shorter than 3 days), means that somehow the process involved in the planetary migration makes the planet "stop" at a distance corresponding to this orbital period. To explain this fact, several ideas have been presented. These invoke different mechanisms like e.g. a magnetospheric central cavity of the accretion disk (once the planet gets into this cavity it will no longer strongly interact with the disk and consequently stops the migration), photo-evaporation, tidal interaction with the host star, or Roche-lobe overflow of the young inflated giant planet (processes resulting in an increase of the orbital radius of the planet, thus opposing the migration tendency)[3] .

In any case, even if these mechanisms are able to explain how the shorter period planets have stopped migration, they do not explain how the longer period ones (like Jupiter itself) did not migrate to distances closer to their host stars. The key to this might have to do with a combination of parameters, like the disk masses, lifetimes, viscosities, and initial planetary masses and/or number of bodies formed, that will affect the final orbital configuration of a planet. Some of these parameters are not well known (maybe the planetary formation itself is controlling them), something that complicates the discussion.

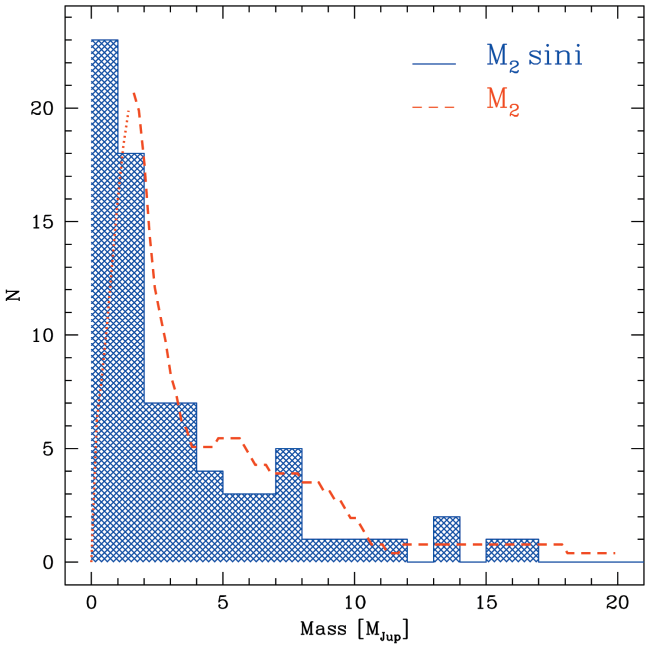
The Mass Distribution

Very important information is brought to us by the analysis of the mass spectrum of the planetary companions. In particular, a plot showing the mass distribution of companions to solar-type stars (as shown in Figure 2), shows a clear discontinuity for the mass regime between about 30 and 50 times the mass of Jupiter: there are basically no companions found to date having those masses. This result is even more striking if we note that the radial-velocity

[2]For a complete and updated list of the known exoplanets, see e.g. table at http://obswww.unige.ch/exoplanets.

[3]Planets migrating more than this approximate limit might "simply" also evaporate/transfer material to the host star, and thus disappear or become too low-mass to be detected.

Figure 3: Distribution of exoplanet masses. The histogram represents the observed minimum mass distribution, while the red line represents the statistical true planetary mass distribution resulting from a deconvolution of the unknown orbital inclinations. The distribution reaches "zero" at a mass of about 10 times the mass of Jupiter, which probably corresponds to the upper limit for the mass of a giant planet. The nature of the objects with masses between 10 and ~17 times the mass of Jupiter is still an open question. As in Jorissen et al. (2001).



technique is more sensitive to massive companions than to their lower mass counterparts.

This gap, usually called the "brown dwarf desert", separates the low mass "planetary" companions from their high mass "stellar" counterparts, and is probably telling us something very important about the physical processes involved in the formation of these two populations: stars, even the low mass ones, are thought to be formed as the result of the gravitational collapse and fragmentation of a cloud of gas and dust. On the other hand, a planet forms in a circumstellar accretion disk.

More information is provided if we analyse the shape of the distribution for the planetary mass regime (Fig. 3). This distribution is observed to decrease smoothly with increasing mass, reaching "zero" at about 10 Jupiter masses (Jorissen et al. 2001). This limit is clearly not related to the Deuterium-burning mass limit of ~13 M_{Jup}, sometimes considered as the limiting mass for a planet (this latter value is in fact an arbitrary limit used as a possible "definition", but it is not related to the planetary formation physics). As it was recently shown by several authors (e.g. Jorissen et al. 2001), this result is not an artefact of projection effects (the unknown orbital inclination implies that we can only derive a minimum mass for the companion from the radial-velocity measurements), but a real upper limit for the mass of the planetary companions discovered so far.

The Period-Mass Relation

Recent results have also unveiled some interesting correlations between the planetary mass and its orbital period. In fact, there seems to exist a paucity of high-mass planetary companions ($M > 2$ M_{Jup}) orbiting in short period (lower than ~40-days) trajectories. Similarly, there seems to be a lack of long-period and very low-mass planets.

These results are further helping us to understand the mechanisms of planet migration, since they are compatible with the current ideas about planetary orbital evolution (either due to an interaction with the disk or with other companions), that suggest that the higher the mass of a planet, the more slowly (and less) it will migrate.

The Eccentricity

One of the most enigmatic results found to date has to do with the analysis of the orbital eccentricities of the planetary-mass companions. According to the traditional paradigm of planetary formation, a planet (formed in a disk) should keep a relatively circular (low eccentricity) trajectory. Current models shown indeed that the interaction (and migration) of a low mass companion within a gas disk has the effect of damping its eccentricity (Goldreich & Tremaine 1980). However, opposite to expectations, if we look at the eccentricities of the planetary companions we can see that they are spread through values that go from nearly zero to more than 0.9 for the planet orbiting the star HD80606!

In Figure 4 we plot the eccentricity as a function of orbital period for the planetary companions to solar-type stars, as well as for the stellar companions. First of all, it is important to describe the general tendencies observed in the plot. The low eccentricity observed for short-period binaries is the result of a well known effect: the proximity to their primary stars induces tidal interactions that have the effect of damping the eccentricity. Since the tidal effect decreases very fast with distance, above a given orbital period (about 10 days for dwarf star binaries), tidal circularization is no longer effective, and all companions having periods longer than a given value simply keep their "initial" orbital eccentricity.

While both distributions show the signature of tidal effects on the eccentricity, a first glimpse also tells us that there is no clear difference between the two groups of points: stars and planets have a similar distribution in this diagram. This poses the problem of understanding how planetary companions formed in a disk can have the same ec-

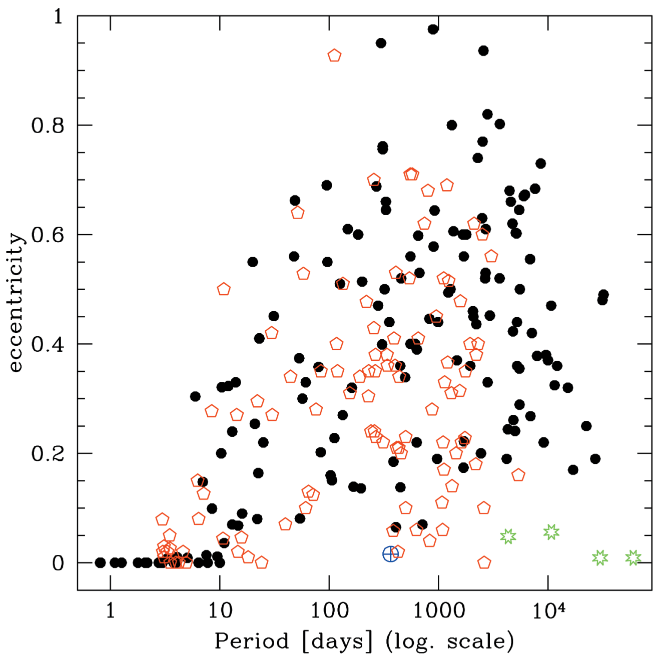


Figure 4: Eccentricity vs. orbital period (in logarithmic scale) for the discovered extra-solar planets (red pentagons), stellar binaries (filled dots), and for the giant planets in our Solar System (green stars). The earth is represented by the usual symbol. Although some long-period exoplanets exist having low values for the eccentricity, most of the systems present much higher eccentricities than those observed for the Solar System giant planets. Possible explanations invoke mechanisms capable of pumping the eccentricity, like gravitational interactions between planets in a multi-planetary system, or with a distant stellar companion.

centricity distribution as their stellar mass counterparts. And how can this be fit into the picture of a planet forming (and migrating) in a disk?

The explanation for these facts may be other processes capable of exciting the eccentricity of the planetary orbits. These include the interaction between planets in a multiple system or between the planet and a disk of planetesimals, the simultaneous migration of various planets in a disk, or the influence of a distant stellar companion. All or at least some of these physical processes might play an important role in defining the "final" orbital configuration.

Although still not clear, a close inspection of Figure 4 permits us to find a few differences between the eccentricities of the stellar and planetary companions. In particular, for periods in the range of 10 to 30 days (clearly outside the circularization period by tidal interaction with the star), there are a few planet hosts having very low eccentricity, while no stellar binaries are present in this region. The same and even stronger trend is seen for longer periods, suggesting the presence of a group of planetary companions with orbital characteristics more similar to those of the planets in the Solar System (with low eccentricity and long period). On the other hand, for the very short period systems, we can see some planetary companions with eccentricities higher than those found for "stars". This features may be telling us that different formation and evolution processes took place: for example, the former group may be seen as a sign for formation in a disk, and the latter one as an evidence of the influence of a longer period companion on the eccentricity.

Clues from the Planet Hosts: the Stellar Metallicity

Up to now we have been reviewing the results and conclusions obtained directly from the study of the orbital properties and masses of the discovered planets. But another fact that is helping astronomers understand the mechanisms of planetary formation has to do with the planet host stars themselves. Indeed, they were found to be particularly metal-rich, i.e. they have, on average, a higher metal content than the stars without detected planetary companions (see Santos et al. 2001 for the most recent results) – see Figure 5.

A possible and likely interpretation of this may be 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.

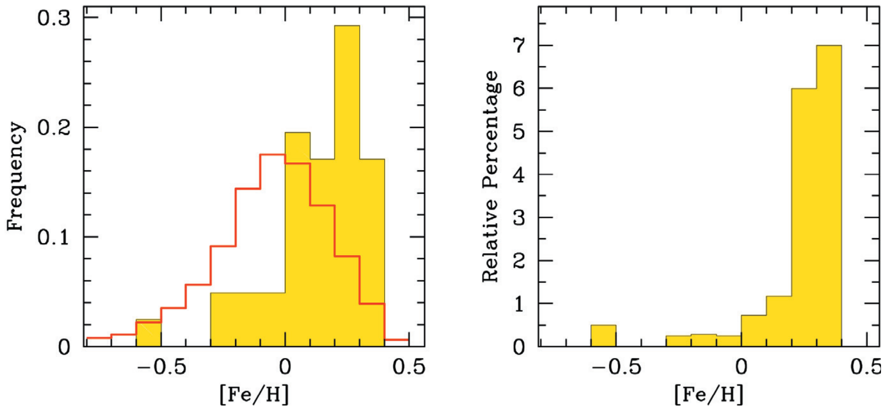


Figure 5: Left*: Metallicity ([Fe/H]) distributions for stars with planets (yellow histogram) compared with the same distribution for field dwarfs in the solar neighbourhood (open red histogram). In this panel, both distributions are normalized by the total number of points. The [Fe/H] scale is logarithmic, and the Sun has by definition [Fe/H] = 0. Most planet hosts are more metal-rich than our Sun;* Right*: the percentage of stars that have been found to harbour a planet for each metallicity bin, plotted as a function of the metallicity. This plot clearly shows that the probability of finding a giant planet increases with the metallicity of the star. As in Santos et al. (2001).*

Boss (1997) has suggested that besides the core accretion scenario (see introduction), giant planets might also be formed as a result of disk instability processes: by the formation and condensation of clumps of gas and dust in the protoplanetary disk. This process is, however, not very dependent on the metallicity. In other words, if the disk-instability models were the most important mechanism involved in the formation of giant planets, we should not expect to see a strong dependence on the rate of planet detection as a function of the metallicity. The huge dependence observed is thus probably a sign that the core accretion scenario is the important mechanism involved in the formation of giant planets.

It is, however, important to stress that it is not precisely known how the metallicity is influencing the planetary formation and/or evolution; for example, the masses of the disks themselves, which can be crucial to determine the efficiency of planetary formation, are not known observationally with enough precision.

A Case of Stellar "Cannibalism"

Recent observations also suggest that planets might be engulfed by their parent stars, whether as the result of orbital migration, or e.g. of gravitational interactions with other planets or stellar companions. Probably the clearest evidence of such an event comes from the detection of the lithium isotope ^{6}Li in the atmosphere of the planet-host star HD 82943 (Israelian et al. 2001). This fragile isotope is easily destroyed (at only 1.6 million degrees, through (p,α) reactions) during the early evolutionary stages of star formation. At this stage, the proto-star is completely convective, and the relatively cool material at the surface is still deeply mixed with the hot stellar interior (this is not the case when the star reaches its "adulthood"). ^{6}Li is thus not supposed to exist in stars like HD 82943, and the simplest and most convincing way to explain its presence is to consider that planet(s), or at least planetary material, have fallen into HD 82943 sometime during its lifetime.

The most recent and detailed analysis seems to clearly confirm the presence of this isotope. The question is then turned to know whether this case is isolated or if it represents a frequent outcome of the planetary formation process. How much can this process increase the observed metallicity of the planet hosts? Current results suggest that at least the degree of stellar "pollution" is not incredibly high (Santos et al. 2001).

Black Sheep

When measuring the spectrum of a star we are obtaining the integrated light of the whole stellar disk, and gathering photons coming from different points in the stellar surface. Each individual point has its own spectrum, with a different Doppler shift that is a function of the velocity field in that specific region of the stellar photosphere. As a consequence, any phenomenon capable of changing the velocity field of a given region in the stellar surface will change the global spectrum Doppler shift, and consequently the measured radial-velocity.

This result has an important impact when dealing with radial-velocity measurements: the radial-velocity technique is not sensitive only to the motion of a star around the centre of mass of a star/planet system, but also to eventual variations in the structure of the stellar surface.

In fact, phenomena such as stellar pulsation, inhomogeneous convection or the presence of dark spots (e.g. Saar

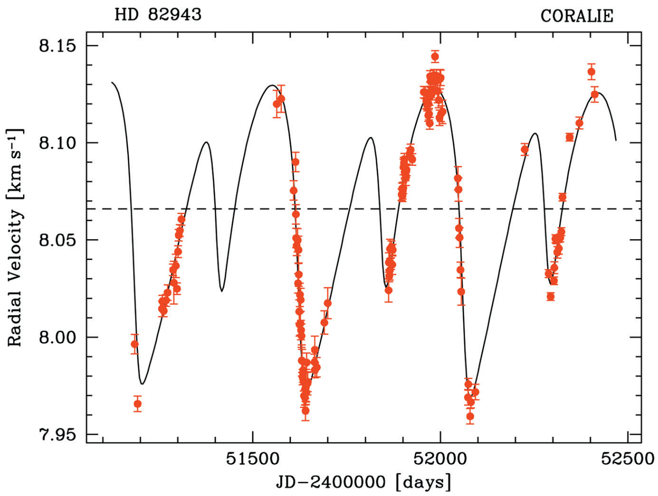


Figure 6: Radial-velocity measurements and best 2-planet Keplerian solution for HD 82943. The radial-velocity measurements show that this star has a system of two resonant planets, orbiting it with periods of ~ 220 and 440 days, respectively. This same star was found to have ^{6}Li in its atmosphere, a signature of possible planet engulfment (Israelian et al. 2001).

& Donahue 1997) are expected to induce radial velocity variations. Furthermore, contamination from the spectrum of other stellar companions can also induce spurious radial-velocity signals. These cases can prevent us from finding planets (if the perturbation is larger than the orbital radial-velocity variation), but perhaps more importantly, they might give us false candidates if they produce a periodic signal (e.g. a rotating stellar spot). The radial-velocity technique is thus most efficient for low chromospheric activity single "old" dwarfs.

A few good examples of spurious periodic radial-velocity variations can be found in the literature. The first to be described was the periodic signal observed for the dwarf HD 166435, that was shown to be due to the presence of a dark spot rather than to the gravitational influence of a planetary companion.

At the current (and increasing) level of precision obtained using the radial-velocity techniques, such kinds of examples might become more and more common. It is thus very important to develop ways to disentangle e.g. activity-related phenomena from real planetary candidates. Such methods might be based on the study of the shape of the spectral lines (usually called the "bisectors"), the photometric variability of the star, and/or of chromospheric activity indexes. This is very important for projects like HARPS, for which the barrier of the 1 ms^{-1} will be achieved.

Guidelines for the Future

The study of extra-solar planetary systems is just beginning. After only 7 years, we can say that at least 5% of solar-type dwarfs have giant planetary companions in relatively short period orbits ($\leq$ 3 years). However, and as we have seen in the previous sections, many interesting but troubling problems still await a solution. In fact, the newly-found planets have clearly disturbed the long-standing theories of giant planetary formation and evolution. The definition of a planet itself is currently under debate.

To solve this problem, there are high expectations from new or soon-to-be available instruments (see the paper on the HARPS spectrometer in this issue). The incredible precision gain achieved by these radial-velocity "machines" will be crucial in this aspect. But what are exactly the important lines of study to follow? And what kind of answers can we expect in the next few years?

Increasing the Statistics

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 formation and evolution of planetary systems. We no longer have the Sun as the only example, and today we have to deal with the peculiar characteristics of the "new" extra-solar planets: a huge variety of periods, eccentricities, masses.

To clear up current uncertainties we need more data. Only a large and statistically uniform set of data may enable us to clarify the current situation. In this sense, the hundreds of new planets expected to be discovered in the next few years will have a very important outcome.

Lower and Lower Masses

One clear result of the increase in precision of the current and future radial-velocity surveys is the ability to find lower-mass planets.

As we have seen above, the mass function for planetary companions around solar-type stars is rising toward the low-mass regime. But given that the radial-velocity technique is more sensitive to the more massive companions, the lower mass bins in the plot of Figure 2 are definitely not well represented. How then does this function behave for the lower-mass regime? What is the minimum mass of a giant planet? How does this depend on the orbital period?

The increase in long-term precision, and the continuation of the current high-precision radial-velocity programmes, will also give us the opportunity of finding more and more long-period planets. Current models predict that the planetary formation and evolution processes should produce more long-period planets than their short period counterparts. In fact, the current surveys are just starting to discover exo-planets with periods comparable to the ones found for the Solar System giants. This is an essential goal in order to improve the statistics of these objects, and to check if the Solar System is anomalous or common.

Of course, other problems will arise and become more important as a consequence of the dramatic increase in precision. In particular, the intrinsic stellar radial-velocity "jitter" produced by e.g. chromospheric activity related phenomena (e.g. Saar & Donahue 1997) might impose serious (and still unknown) limits on the final precision, and on the consequent ability to find very low-mass (and long-period) systems. This is particularly true for the youngest stars. Some effort should thus be put into the development of diagnostics capable of confirming the planetary nature of the radial-velocity signal. Furthermore, we might even imagine that the spurious radial-velocity variations caused by activity might be modelled and corrected, leaving only the real gravitational effects on the signal.

Planets Around M Dwarfs

Although more than 100 exoplanet candidates are now in the lists, only two planetary companions around M dwarfs have been detected (both in the solely system Gl 876). The very low number of M-dwarf planetary companions can in fact be largely explained by observational biases: the very low mass dwarfs are faint and it is difficult to obtain accurate radial velocities for them.

However, to constrain the various scenarios of planetary-system formation and evolution, it is now crucial to obtain better statistics for planets around the most numerous stars in our galaxy. M dwarfs compose 80% of the main sequence stars. How many of them have planets? How these planets differ from those orbiting the more massive G dwarfs is totally unknown. These questions await the future capabilities of instruments like HARPS.

The Chemical Link

Planet host stars seem to be, on average, particularly metal-rich. This interesting result probably reflects the importance the quantity of available rocky material in the disk has on the formation of giant planets.

As discussed above, this link might hold the key to understanding how giant planets are formed. The two competing theories (core accretion and disk instability) should have different sensitivities to the metallicity. If most planets were formed by the latter of these two processes we should not expect any special metallicity sensitivity.

Although the metallicity trend is clearly seen (Santos et al. 2001), there are nevertheless a few planet hosts that are particularly metal poor (see e.g. case of HD 6434). How can this be explained? One elegant way of solving this puzzle is to look for the frequency of planets around metal-poor halo dwarfs. If, as expected, no planetary mass objects are found around such a sample of stars, then the disk instability model is clearly put into question. However, if some are found, giant planets might be formed by different processes.

There are also some traces of stellar "pollution" among the planet host stars (Israelian et al. 2001). This opens the question of understanding how much planetary material might fall into the convective envelope as a consequence of the planetary formation process itself. How much can this change the metallicity of the star? If important, this could have consequences even for studies of the chemical evolution of the galaxy.

Although current results seem to refute any strong generalized stellar pollution among planet hosts, it is important to cross-check. One interesting way of addressing this problem might then be the study and comparison of the chemical contents of stars in visual binary systems composed of similar spectral type solar-type stars, one (or both) of which having planetary-mass companions. Strong differences found would be interpreted as a sign that stellar pollution is quite common. However, only one clear case has been studied to date: the double visual system 16 Cyg A and B, where the B component is known to harbour a planet. This case does not show any clear difference in the iron abundance, while a curious lithium abundance difference is found.

Transit Candidates

Another important result of instruments like HARPS will be their ability to follow up planetary-like transit signatures detected by photometry.

There are currently more than 20 groups around the world trying to look for signatures of the presence of planets around field dwarfs by looking for the brightness dimming as a putative planet crosses its disk. In spite of the efforts, only very few results have been announced, and none of these was confirmed to have a planetary origin. The only clear case of a real planetary transit detected so far was found for the star HD 209458, a dwarf that was previously discovered to host a very-short period planetary companion (Charbonneau et al. 2000).

This detection, and the subsequent related studies, have had an enormous impact for the understanding of these systems. For example, it was possible to estimate the mean density of the planet, and to prove that it is orbiting in the same direction and plane as the star's equator.

In the near future we can expect that other such events might be brought to light. In particular, many hundreds of photometric transit candidates are expected from space missions like COROT, Kepler or Eddington. However, based only on photometry we cannot determine whether the observed transiting body is a planet or simply a low-mass star (since the effect is of similar magnitude because of the large degeneracy of the radius of these objects). The follow-up of the photometric observations by radial-velocity surveys is thus essential and will permit us to obtain the real mass of the planet.

With such data we can hope to derive empirical relations between variables such as the planet's mean density and its distance from the star, its mass, and the stellar metal abundance. In this sense it is important to say that the very high precision of HARPS, together with the relatively large aperture of the ESO 3.6-m telescope, will play an important role, since it will give the opportunity to obtain masses (or at least meaningful upper limits) for the least massive planets detected by the photometric missions.

Multiple Systems: Dynamical Interactions

Among the many planets that are expected to be found, some will surely belong to multi-planetary systems. Today, only about 10 such cases are known, but many stars that are already known to harbour a planet also show systematic trends in radial velocity, indicating that at least a second companion is present in the system. While for the majority of cases this tendency might be simply due to the presence of low-mass stellar companions, in some others they might be the telltale signatures of a multi-planetary system. The gain in precision with instruments like HARPS will definitely permit us to search the already known planet hosts for other planet-mass companions, and to increase the number of known multiple systems.

There is in fact much interesting information that can come from these cases. Current results have shown that planets in multiple systems come frequently in resonant orbits (see e.g. HD82943 – Figure 6). This is telling us a lot about the formation and migration of the exoplanets.

On the other hand, the strong interaction between planets in such systems will be reflected as an observable evolution of their orbital parameters. A dynamical analysis of this will give us the opportunity to obtain information on the masses and relative orbital inclinations for the companions.

Planets in Binaries

To date, several planets have been discovered in known multiple stellar systems. Moreover, a fraction of stars known to host planets exhibit a drift in the γ-velocity indicating the presence of an additional distant companion.

These observations show that despite the gravitational perturbation of the stellar companion, planets may form and survive around stars in multiple systems. The properties of such planets hold important clues on the mechanisms of planetary formation. For example, according to the standard core accretion model of planetary formation, a giant planet is formed by the accretion of gas around a ~ 10 earth mass core of rocky material. This is supposed to take place at distances comparable to the Jupiter–Sun separation (~5 A.U.). Opposing this model, Boss (1997) has proposed that giant gaseous planets might also be formed from the condensation of clumps resulting from gravitational instabilities in the disk. How can we distinguish these two scenarios?

One of the keys may come from the study of planets in binaries. The presence of a stellar companion possibly plays an important role in the formation of planets. It has been shown, for example, that a stellar companion can truncate the proto-planetary disk at a radius that depends mainly on the distance between the two stars. If so, and considering the core accretion scenario, we should not be able to see planets around stars members of binary systems that are closer than a given limit. How close can a star have a companion and still have planets? The answer to this question is very important to understand how giant planets are formed.

Concluding Remarks

As the planet search programmes are on their way, many more planetary companions are expected to be discovered in the next few years. Many hopes are now placed on instruments like HARPS, that will provide radial velocities of stars with a precision of 1 ms^{-1} or better. This will give us the opportunity to dramatically improve the samples.

Other major contributions will come from future space missions like COROT, Eddington, or Kepler, which will unveil thousands of short-period planets around stars in the solar neighbourhood. And, of course, the use of high-precision astrometric measurements with instruments like the VLTI or the Keck interferometer will survey "nearby" stars for long-period systems. Altogether, these coming observational facilities will definitely help us to construct a new and more complete view of how planetary systems are born and how they evolve.

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FIRES: Ultradeep Near-Infrared Imaging with ISAAC of the Hubble Deep Field South

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1. Introduction

Between October 1999 and October 2000 an undistinguished high-galactic latitude patch of sky, the Hubble Deep Field South (HDF-S), was observed with the VLT for more than 100 hours under the best seeing conditions. Using the near-infrared (NIR) imaging mode of the Infrared Spectrometer and Array Camera (ISAAC, Moorwood 1997), we obtained ultradeep images in the J_s (1.24 μm), H (1.65 μm) and K_s (2.16 μm) bands. The combined power of an 8-metre-class telescope and the high-quality wide-field imaging capabilities of ISAAC resulted in the deepest ground-based NIR observations to date, and the deepest K_s-band in any field. The first results are spectacular, demonstrating the necessity of this deep NIR imaging, and having direct consequences for our understanding of galaxy formation.

The rest-frame optical light emitted by galaxies beyond $z \sim 1$ shifts into the near-infrared. Thus, if we want to compare $1 < z < 4$ galaxies to their present-day counterparts at similar intrinsic wavelengths – in order to understand their ancestral relation – it is essential to use NIR data to access the rest-frame optical. Here, long-lived stars may dominate the total light of the galaxy and the complicating effects of active star formation and dust obscuration are less important than in the rest-frame ultraviolet. This therefore provides a better indicator of the amount of stellar mass that has formed. Compared to the selection of high-redshift galaxies by their rest-frame UV light, such as in surveys of Lyman Break Galaxies (LBGs, Steidel et al. 1996a,b),

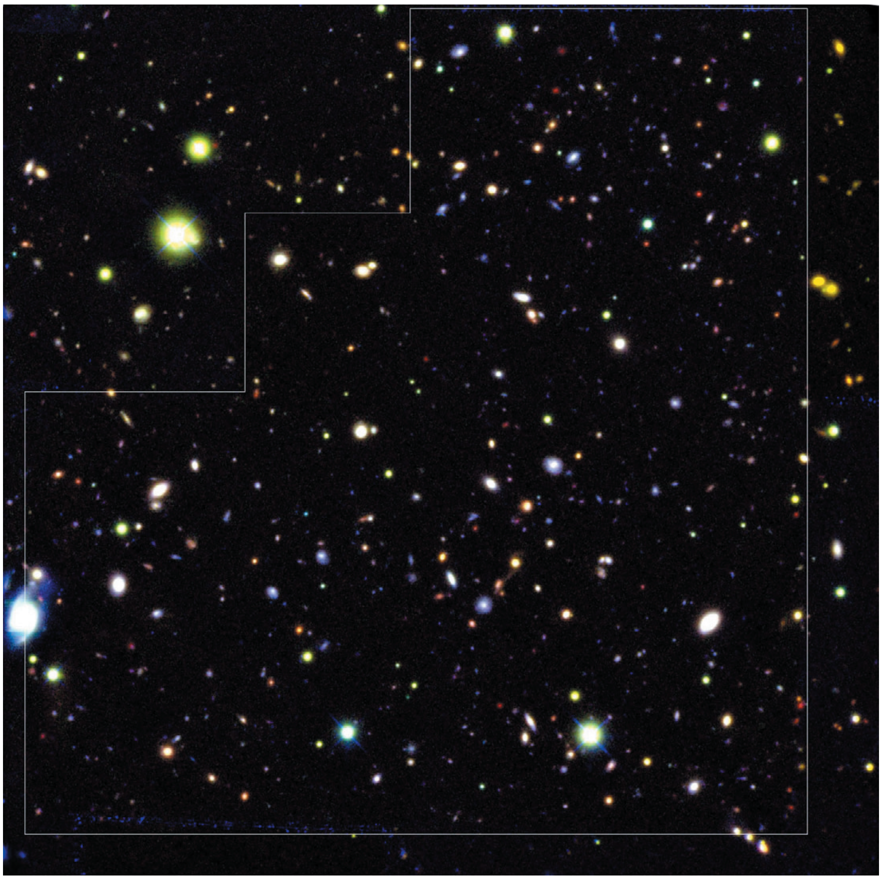

Figure 1: Three-colour composite image of the ISAAC field on top of the WFPC2 main-field, outlined in white, and parts of three WFPC2 flanking fields. The field of view is approximately 2.5 × 2.5 arcminutes and North is up. The images are registered and smoothed to a common seeing of FWHM ≈ 0.46″, coding WFPC2 I_{814} in blue, ISAAC J_s in green and ISAAC K_s in red. There is a striking variety in optical-to-infrared colours, especially for fainter objects. A number of red sources have photometric redshifts $z > 2$ and are candidates for relatively massive, evolved galaxies. These galaxies would not be selected by the U-dropout technique because they are too faint in the observer's optical.