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PLANETS IN MULTIPLE-STAR SYSTEMS:PROPERTIES AND DETECTIONS

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RESUMEN

Se presentan brevemente las propiedades orbitales de los planetas extrasolares, y se comparan con las de las estrellas binarias. Se discuten las similitudes y las diferencias entre ambas. Entre los más de 115 planetas extrasolares descubiertos hasta ahora, 19 orbitan en torno a una componente de un sistema binario. Discutimos las propiedades de esta sub-muestra, y las comparamos con las de los planetas que orbitan estrellas sencillas. Se observan diferencias en la distribución de masas-períodos-excentricidades; los exoplanetas con $m_2 \sin i > 2\,\mathrm{M_{Jup}}$ y $P \leq$ 40-100 días están en binarias, y presentan excentricidades bajas. En el escenario de migración, estas características se explican tentativamente a la luz de simulaciones recientes de las interacciones planeta-disco, las cuales muestran tasas crecientes de acreción y migración en presencia de la perturbación de una compañera estelar cercana. También se presentan distintos enfoques observacionales que tienden a mejorar la estadística disponible, aún pobre. Un resultado importante es la detección de una compañera planetaria en el sistema triple HD 41004.

ABSTRACT

Orbital properties of extra-solar planets are briefly recalled and compared with equivalent features of stellar binaries. Similarities and differences are discussed. Among the more than 115 extra-solar planets discovered to date, 19 are orbiting a component of a binary system. We discuss the properties of this subsample and compare them with the equivalent characteristics of planets around single stars. Differences in the mass-period-eccentricity distributions are observed: exoplanets with $m_2 \sin i > 2\,\mathrm{M_{Jup}}$ and $P \leq$ 40-100 days are in binaries and present low eccentricities. In the context of the migration scenario, these characteristics are tentatively explained in the light of recent simulations of planet-disk interactions showing an increased accretion and migration rates of planets in case an additional perturbing close stellar companion is present in the system. Finally, different observational approaches to find planets in long-period spectroscopic binaries aiming to improve the still poor available statistics are presented. An important result is the detection of a planetary companion in the HD 41004 triple system.

Key Words: **BINARIES: GENERAL — STARS: PLANETARY SYSTEMS — TECHNIQUES: RADIAL VELOCITIES**

1. INTRODUCTION

There are basically two ways of looking at exoplanet properties in a colloquium dedicated to multiple star systems. First, we will compare the orbital properties of planetary systems with those of stellar binaries. This will allow us to recall some of the main statistical characteristics of the known extra-solar planet sample, emphasizing the differences and similarities with stellar binaries. From the observational point of view, the available sample of known extra-solar planets is becoming large enough to sketch out a reliable picture of their orbital properties (Marcy et al. 2003; Udry, Mayor & Queloz 2003, Udry, Mayor & Santos 2003).

The second approach, mainly developed in this contribution, focuses on the properties of the subsample of extra-solar planets orbiting one of the components of binary- or multiple-star systems. Nineteen candidates are known from different programmes. They will be presented in Sect. 3. Although the sample is still very small, we are starting to see some statistical trends which may introduce interesting constraints on planetary formation scenarios (Eggenberger, Udry & Mayor 2004a, 2004b; Udry, Eggenberger & Mayor 2004). In particular, the *period-mass-eccentricity* distributions are presented in Sect. 4, in comparison with similar distributions of planets orbiting single stars. The results are discussed in the light of recent simulations of planet formation and migration, described in Sect. 5.

Even if the detection and characterization of planets in binaries are more difficult to carry out

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than the study of planets around single stars, they are worth doing because of the new constraints and information they can provide about planet formation and evolution. To illustrate our effort in improving the available statistics, we describe in Sect. 6 the programme dedicated to the search for short-period planets in spectroscopic and close visual binaries.

2. PLANETS VS STELLAR BINARIES

Rapidly after the first extra-solar planet discoveries, it became clear from the minimum mass distribution that the emerging new very low-mass population did not compose the tail of the distribution of stellar secondaries to solar-type stars. The bimodal distribution emphasizing the so-called *brown-dwarf desert* still remains the main indication for different formation/evolution mechanisms for the 2 populations (Fig. 2, upper left).

With the increasing time baseline of the searches, new interesting features of the period-mass distribution of exoplanets are emerging (Udry, Mayor & Santos 2003, Zucker & Mazeh 2002). First, there is a clear lack of massive planets with short periods. Also, the number of detected planets increases with period (Fig.2, upper right). We thus expect a large number of planets at larger separations. Furthermore and related to the BD-desert problem, the maximum mass of the detected planets is also increasing with period. More massive planets are found further out (Fig. 2, lower left). Taking into account the results of large all sky mapping in the near IR bands (Denis, 2Mass) that show a large number of BD companions at large separations, the BD desert tends thus to fill up, from both stellar and planet sides, when we consider companions of longer and longer periods. This feature makes a planet-BD differentiation in the 10-20 M_{Jup} mass range more difficult.

Another striking similarity between planets and binaries appears when looking at the $(e, \log P)$ diagram for the two populations (Fig. 2, lower right). This similarity has often been brought up as a challenge for different formation scenarios, although some differences can clearly be pointed out (Mayor & Udry 2000). The most important of them is the pile-up of short-period planets around 3 days (see Fig. 1, upper right), a “wall” that is not observed for binaries. This feature is strongly indicative of a stopping mechanism for the migration of giant planets.

In addition, more and more longer-period quasi-circular orbits are being discovered, unveiling candidates resembling the giant planets in the solar system.

TABLE 1

PLANETS IN MULTIPLE-STAR SYSTEMS

Star	a_{bin} [AU]	a_p [AU]	$M_p \sin i$ [M_J]	e_p	Notes
HD 40979	~6400	0.83	3.28	0.25	CPM
Gl 777 A	~3000	4.8	1.32	0.48	CPM
HD 80606	~1200	0.469	3.90	0.927	CPM
55 Cnc	~1065	0.115	0.84	0.02	CPM
		0.241	0.21	0.34	
		5.9	4.05	0.16	
16 Cyg B	~850	1.66	1.64	0.68	CPM
Ups And	~750	0.059	0.69	0.012	CPM
		0.829	1.89	0.28	
		2.53	3.75	0.27	
HD 178911 B	~640	0.32	6.292	0.124	CPM
HD 219542 B	~288	0.46	0.30	0.32	CPM
Tau Boo	~240	0.05	4.08	0.01	VO
HD 195019	~150	0.14	3.50	0.0	CPM
HD 114762	~130	0.35	11.03	0.34	CPM
HD 19994	~100	1.3	2.0	0.2	VO
HD 41004 A	~23	1.33	2.5	0.39	SB
γ Cep	~22	2.03	1.59	0.2	SB
Gl 86	~20	0.11	4.0	0.046	SB,CPM

Note: CPM stands for common proper motion, SB for spectroscopic binary and VO for visual orbit. References about the planet detection and binary characteristics for these candidates are given in Eggenberger et al. (2004a).

In summary, on the one hand, we observe several properties specific to the exoplanet population that are interpreted as fossil traces of their formation and/or evolution. On the other hand, the planet and binary populations exhibit some similar features, the origin of which has to be understood. Further information to answer this question will be brought by the increase of the available statistics thanks to new planet detections, and by the emerging properties of subclasses of exoplanets with particular properties. Such subclass, consisting of planets in multiple-star systems (Eggenberger et al. 2004a) that will be discussed in the following sections.

3. EXOPLANETS IN MULTIPLE STAR SYSTEMS

Some of the extra-solar planets discovered to date are orbiting a component of a multiple stellar system. Planets have been found around stars known to be part of a wide common proper motion pair (CPM), known to be in a visual binary (some with tentative orbits, VO) or in a “closer” spectroscopic binary (SB). Alternatively, searches for faint companions to stars hosting planets have revealed a few

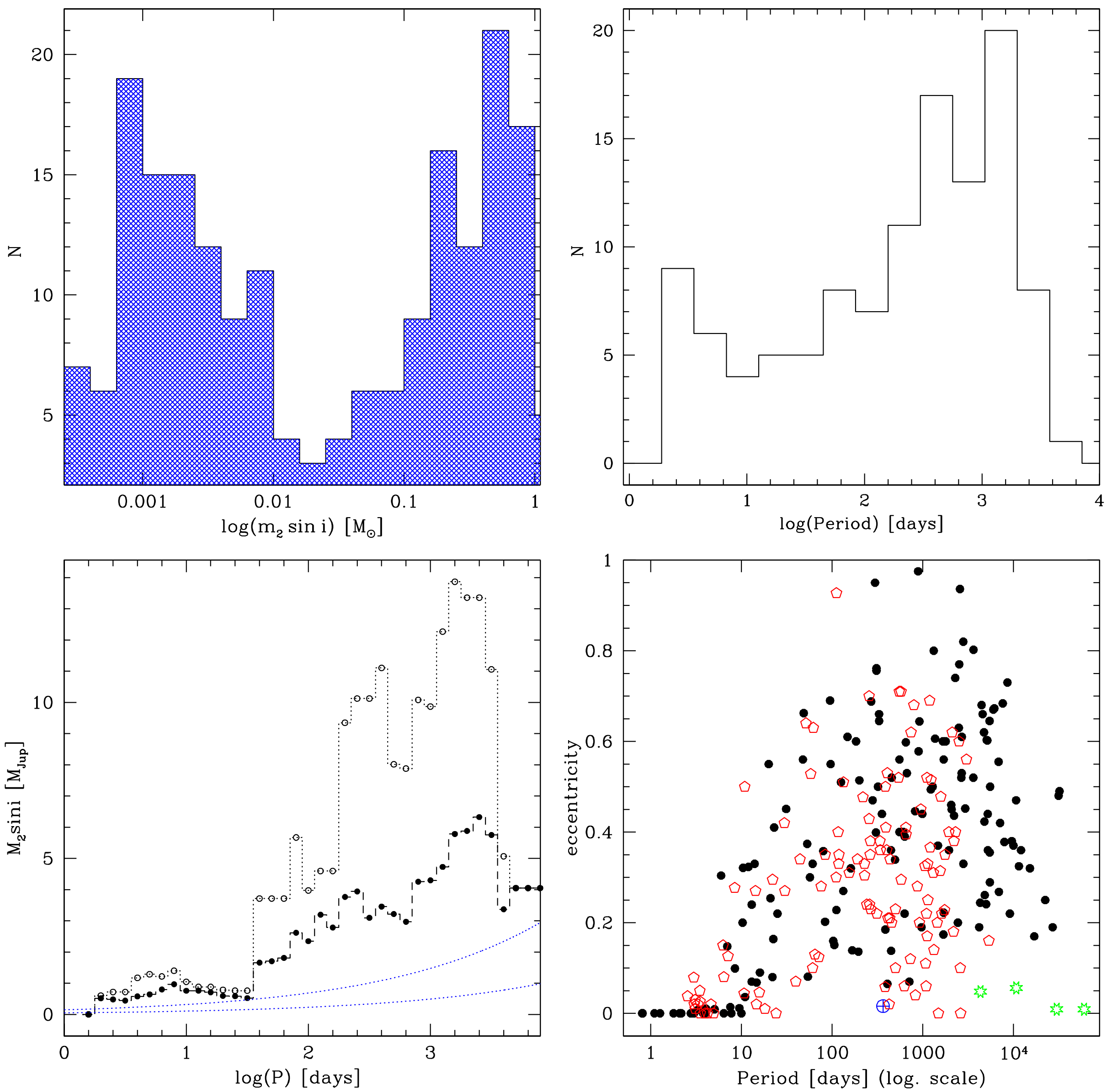

Fig. 1. *Upper left:* Mass distribution of secondaries to solar-type stars. The 2 peaks for planets and stellar binaries clearly emphasize the so-called *brown-dwarf desert*. *Upper right:* Distribution of planet periods. A shortage of planets with periods between $\sim$10-100 d forms a "valley" in the distribution. *Lower left:* Mean mass (filled circle) or highest mass (average on the 3 highest values, open circles) of planets in period smoothing windows. More massive planets are found further out. *Lower right:* $(e, \log P)$ diagram for planets (open pentagons) and stellar binaries (filled circles). Solar system planets are indicated as well (Earth- and star-like symbols).

new systems. Table 1, which summarizes the information known about these systems, shows that giant planets can form and survive in certain types of multiple-star systems. Note that the 20 to 100 AU separation range for the binary separation ($a_{\rm bin}$) is under-represented.

4. PROPERTIES OF EXOPLANETS IN BINARIES

Though the sample of planets found in multiple-star systems is not large, a preliminary comparison between their characteristics and the properties of planets orbiting isolated stars can be made. Here, we will discuss the mass-period and the eccentricity-

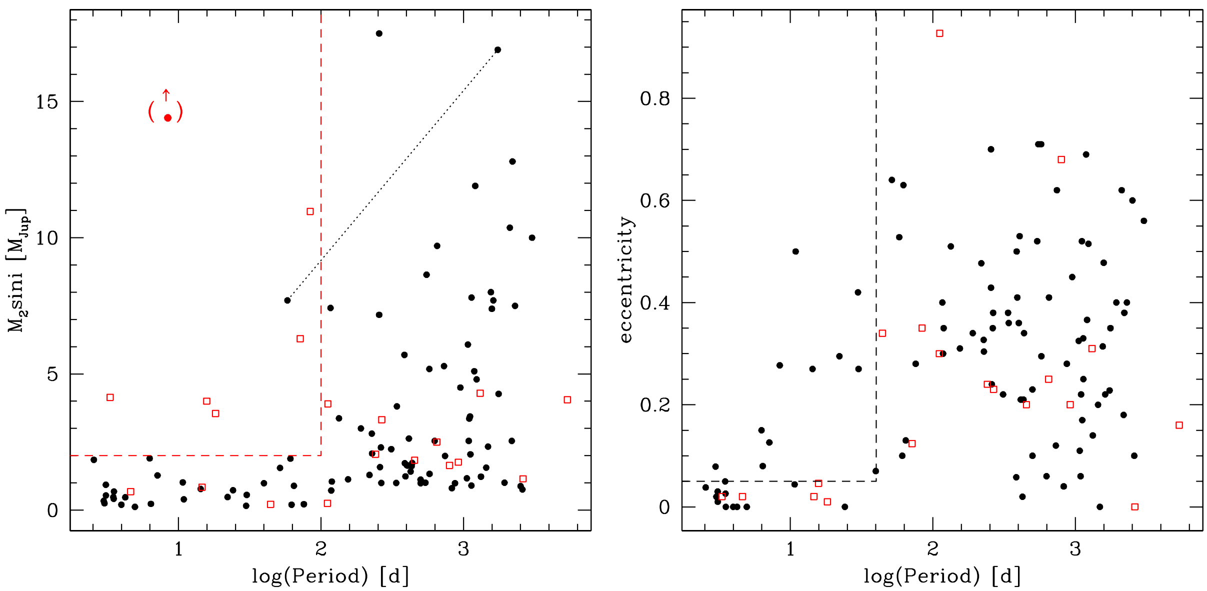

Fig. 2. *Left:* Planetary minimum mass versus orbital period for planets orbiting single stars (filled circles) or a stellar binary component (open squares). *Right:* Period-eccentricity diagram for the same populations (same symbols).

period diagrams for extra-solar planets, focusing on the possible differences between the two populations.

4.1. *The mass-period distribution*

Figure 3 (left) shows the distribution of the extra-solar planetary candidates in the $M_2 \sin i$-$\log P$ plane. Two interesting features emerge from this plot: there are no short-period extra-solar planets with a mass $M_2 \sin i \gtrsim 5\,\mathrm{M_{Jup}}$, and the most massive short-period planets are found in multiple-star systems (Zucker & Mazeh 2002; Udry, Eggenberger & Mayor 2004, Udry, Mayor & Santos 2003, Eggenberger et al. 2004a, 2004b). Indeed, planetary candidates with a mass $M_2 \sin i \gtrsim 2\,\mathrm{M_{Jup}}$ and a period $P \lesssim 100$ days are all orbiting a component of a multiple stellar system[3].

The orbital period below which there are no massive planets orbiting single stars is not well defined. The two populations of planets are somewhat mixed together for periods between 40 and 150 days. The paucity of massive short-period planets cannot be attributed to observational selection effects since these planets are the easiest to detect. Moreover, even if the sample of planets orbiting a component of a multiple-star system is small and strongly incomplete, the presence of a few candidates in a zone of the diagram where there are no other planets is significant (Zucker & Mazeh 2002).

4.2. *The eccentricity-period distribution*

The distribution of the extra-solar planetary candidates in the e-$\log P$ plane is plotted again in Fig. 3 (right). In this diagram, we note that all the planets with a period $P \lesssim 40$ days orbiting in multiple-star systems have an eccentricity smaller than 0.05, whereas longer period planets found in multiple-star systems can have larger eccentricities.

Some of the very short-period planets are so close to their parent stars that tidal dissipation in the planets could have circularized their orbits, even if they were originally eccentric (Rasio et al. 1996). For longer periods, the orbits are not necessarily circularized, and any eccentricity is possible. For the three planets with a period between 10 and 40 days orbiting in multiple-star systems, the circularization time (due to tidal dissipation in the planet) is $\tau_c \gtrsim 10^{12}$ years. This is clearly too long to explain the low eccentricities of these planets. Can available theoretical studies on planets in binaries help us to understand these observed properties?

5. PLANET FORMATION SCENARIOS

Several approaches were followed by theoreticians in order to assess how a stellar companion can in-

[3] The only exceptions are: i) HD 162020 b (in parentheses), a probable brown dwarf with an actual mass much larger than its minimum mass (Udry et al. 2002), and ii) HD 168443 b, a member of a system with two massive "planets" (dotted line), probably also brown dwarfs (Udry et al. 2002, Marcy et al. 2001)

fluence the various stages of planet formation and evolution.

– **Giant planet formation in binaries:** Two main mechanisms are proposed to explain giant planet formation: core accretion and disk instability (Pollack et al. 1996; Boss 1997; Mayer et al. 2002). The core accretion mechanism involves runaway gas accretion on a solid core formed at a distance ≥ 3-5 AU from the star (beyond the "ice boundary") where the dust-ice outer layer allows for rapid core agglomeration. In the disk instability model, a gravitationally unstable disk fragments directly into self-gravitating clumps of gas and dust that can contract and become giant gaseous protoplanets.

According to Nelson (2000), the companion has a negative influence on both mechanisms, slowing, or inhibiting altogether, giant planet formation. Boss (1998) claims the opposite, namely that giant planet formation via gravitational collapse is favoured in binaries.

– **Binary-disk interactions:** Transfer of angular momentum between the binary and circumbinary or circumstellar disks leads to a truncation of their inner or outer edges, respectively. The location of the truncation radius is determined by the balance between the gravitational and the viscous torques (Artymowicz & Lubow 1994).

The disk truncation can substantially influence planet formation and evolution.

– **Stability of orbits:** Distant stellar companion can turn the planetary orbit unstable. Holman & Wiegert (1999) have shown that the orbit is stable as long as the stellar companion is not too close. For example, for a binary with $\mu = M_2/(M_1 + M_2) = 0.3$, the largest stable orbit around the primary star is at $r_c = 0.37\,a_{\rm bin}$ for $e_{\rm bin} = 0$ or at $r_c = 0.14\,a_{\rm bin}$ for $e_{\rm bin} = 0.5$.

– **Evolution of an embedded planet in a binary:** Kley (2001) studied the evolution of a giant planet still embedded in a protoplanetary disk around the primary component of a binary system. A $1\,{\rm M_{Jup}}$ planet was placed on a circular orbit at 5.2 AU from a $1\,{\rm M_\odot}$ star. The secondary star had a mass of $0.5\,{\rm M_\odot}$ and an eccentricity of 0.5. The binary semi-major axis was varied from 50 to 100 AU. The simulations showed that the companion altered the evolutionary properties of the planet: the mass accretion rate was increased and the inward migration time was reduced. In the simulations, the planet eccentricity was also modified: it first grew due to the perturbations induced by the secondary star, but then declined because of the damping action of the disk. The final result was a rapid decay of the planet semi-major axis and a damping of the initial eccentricity.

From the different theoretical approaches, we see that a planet can be formed and almost always persist in a binary stellar system. We also expect the secondary star to have an impact on planet formation, at least for close binaries. Kley (2001) has shown that this remains true for the subsequent evolution (migration) of giant planets in binaries. The changes in the migration process induced by a stellar companion (faster migration, enhanced mass accretion rate, eccentricity damping) seem to be in agreement with the observation that the most massive short-period planets are found in multiple-star systems and have very small eccentricities. It should, however, be noticed that several of the binaries known to host planets are probably very different from the ones studied by Kley. The five planets with periods shorter than 40 days orbit in binaries with very different separations (from $\sim$20 to $\sim$1000 AU). It seems unlikely that the perturbations produced by a wide companion would influence the evolution of a protoplanet orbiting at or below a few AU. This, however, deserves further study.

6. ENLARGING THE SAMPLE OF PLANETS IN BINARIES

As previously stated, our knowledge regarding the existence of extra-solar planets in multiple stellar systems is still far from being complete. To fulfil the urgent need of increasing the available statistics, several programmes aiming at detecting and studying planets in binaries have been recently started. None of them are concluded yet, and only preliminary results are available. We will briefly mention here some of the efforts we are pursuing in this direction, mainly our spectroscopic programme searching for giant planets in spectroscopic and close visual binaries.

The reverse approach, searching for stellar companions around stars known to host planets, is also underway with VLT/NACO. This programme is described in Udry et al. (2004).

6.1. *Short-period planets in spectroscopic binaries*

We have started a programme aiming to search for short-period circumprimary giant planets in single-lined spectroscopic binaries (Eggenberger et al. 2003, Udry, Eggenberger & Mayor 2004). This programme will enable us to probe the existence of giant planets in close binaries for which circumstellar disks can be seriously truncated. The results will also possibly allow us to establish the minimal separation for a binary to host circumprimary giant planets and provide observational constraints regarding the formation and subsequent evolution of these planets.

Our sample of binaries is composed of about 100 systems in both hemispheres with periods ranging from approximately 2 to more than 50 years. These binaries have been selected on the basis of different CORAVEL surveys for G and K-dwarfs of the solar neighbourhood (Duquennoy & Mayor 1991, Udry et al. 1998, Halbwachs et al. 2003). For each binary, 10-15 high-precision radial velocity measurements are taken over two observational seasons with the CORALIE or the ELODIE spectrographs. Residual velocities around the Keplerian orbit (for relatively short-period binaries) or around a drift (for longer period systems) are then analyzed and short-period radial velocity variations are searched for.

Preliminary results show for most of the targets a very small dispersion of the high-precision radial velocities (a few m/s), thus ruling out the presence of a short-period giant planet orbiting the primary star. In some cases, however, the measured radial-velocity dispersion is high. The goal is now to reject false alarms among these interesting candidates. A typical case of false alarm is induced by the contamination of the stellar light by the secondary spectrum, when the light ratio of the binary components is larger than $\sim 1\%$. In such cases, the two components have to be disentangled and individual radial velocities obtained. This is possible with 2D cross-correlation schemes such as TODCOR (Mazeh & Zucker 1994). The same problem is encountered with close visual binaries, as described in the following subsection.

6.2. *Probing the close visual binaries: the HD 41004 "quadruple" system*

A very important point for detecting close companions of stars monitored by high-precision radial velocities has been raised recently. Santos et al. (2002) describe the false detection of a Saturn-mass planet orbiting around HD 41004 A with $P = 1.33$ d. They have shown that the false detection was induced by the Doppler-moving spectrum of a faint close spectroscopic binary system (HD 41004 B) superimposed on the primary spectrum. HD 41004 B was visually detected by Hipparcos ($\Delta m \sim 4$ and $\rho = 0.5''$). In such a case, the moving faint spectrum makes the lines of the primary spectrum appear asymmetric, inducing a spurious radial-velocity variation.

This case was treated with a multi-order version of TODCOR (Zucker et al. 2003). The faint binary companion (HD 41004 B) is now confirmed to be a system composed of an M4 dwarf + a $M_2 \sin i = 19\,\mathrm{M_{Jup}}$ companion. Furthermore, the two-dimensional correlation technique provided individual velocities for the two components of the visual binary. The derived velocities revealed that the primary star (HD 41004 A) hosts a $2.3\,\mathrm{M_{Jup}}$ planet (Zucker et al. 2004). Similar cases from our CORALIE planet-search programme are under study.

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DISCUSSION

Mardling – The presence of a binary companion will induce significant eccentricity in the planetary orbit, whether or not it is inclined. This will restrict how close the planet can be to the star.

Udry – Yes, but they are known planets with fairly large eccentricities, e.g., HD 108147 has a 10.9 day period and e = 0.5. On the other hand, there are other possible explanations for the lack of massive planets in short-period orbits. Patzeld & Rauer (2002) invoke instability leading to tidal decay of the planet spiraling into the star, the timescale of which is dependent on the planet mass.

Zinnecker – Can you tell us something about the prospects of finding planets around eclipsing binaries?

Udry – First, planets can be found in eclipsing binaries by monitoring the epochs of the transits. A planetary companion perturbation induces changes in the regular timing of the binary eclipse. There is a search going on in CM Dra (Guinan, 2004). Second, planetary transits are also possible and contributing very important pieces of information (planetary radius, mass, and mean density). In the context of binary stars, I would mention the recently announced OGLE-56 candidates (Kornaki et al., Astro-Ph 2004) because in this case all presented observations (photometric transit and radial velocity measurements) can also be explained by a triple-star configuration composed of a primary plus an eclipsing binary as the secondary. The light will be dominated by the primary so the eclipse will not be deep, and the small-amplitude radial-velocity variation can be explained in the same way as for HD 41004, like I just showed you. The observational proof for such a configuration will be given by line bisector measurements and will be rapidly available thanks to the HARPS spectrograph being installed this week on the 3.6-m ESO telescope at La Silla observatory.

Griffin – The graph of radial velocities of HD 41004 B appears to show evidence that the star is double-lined. The residuals are systematically towards the γ-velocity near the conjunctions.

Udry – First I have to mention that the flux ratio between the A and B components is only 2-3%. Then, that the HD 41004 B velocities are obtained through a bidimensional cross-correlation technique. The positions of the points around the solution are dependent on the precise choice of the template used for HD 41004 B in the correlation. Trying to see something at the level of a few m/s here is certainly overinterpreting the data.

Kaper – Beautiful work! It is (logically) presumed that planets and star(s) form simultaneously. There is, however, evidence that planets can form much later in the evolutionary path of a (binary) system: the planets detected around pulsars. Could it be that planets formed in a binary system (of two "normal" stars) are formed much later in the evolution of the binary system (e.g., due to a phase of Roche-lobe overflow leading to a disk around the mass gainer)?

Udry – That is probably the case, as it is believed that the pulsar planets are formed in the accretion disk during the pulsar formation as you mentioned. However, detecting the planet seems very difficult with radial velocity measurements as the star is probably spun up by the accretion process. Maybe future high-precision photometric facilities (SIM, GAIA) will reveal systems with a white dwarf plus a star hosting a planet. However, even in this case, it will be difficult to prove that the planet did not form at the same time as the star.

Farbiash – Have you found any evidence for the existence of extra-solar systems around binaries?

Udry – There are two known cases of multi-planet systems orbiting one of the components of a binary: 55 Cnc, and υ And. There is no circumbinary planet known to date. But there has been no dedicated search to look for such planets.