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Statistical properties of exoplanets

III. Planet properties and stellar multiplicity

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Abstract. Among the hundred or so extrasolar planets discovered to date, 19 are orbiting a component of a double or multiple star system. In this paper, we discuss the properties of these planets and compare them to the characteristics of planets orbiting isolated stars. Although the sample of planets found in multiple star systems is not large, some differences between the orbital parameters and the masses of these planets and the ones of planets orbiting single stars are emerging in the mass-period and in the eccentricity-period diagrams. As pointed out by Zucker & Mazeh (2002), the most massive short-period planets are all found in multiple star systems. We show here that the planets orbiting in multiple star systems also tend to have a very low eccentricity when their period is shorter than about 40 days. These observations seem to indicate that some kind of migration has been at work in the history of these systems. The properties of the five short-period planets orbiting in multiple star systems seem, however, difficult to explain with the current models of planet formation and evolution, at least if we want to invoke a single mechanism to account for all the characteristics of these planets.

Key words. stars: planetary systems – stars: binaries: general

1. Introduction

Studies of stellar multiplicity among solar-type stars of the solar neighbourhood have shown that about 40% of the G and K dwarfs can be considered to be real single stars (Duquennoy & Mayor 1991; Eggenberger et al. 2003). As the majority of solar-type stars belong to double or multiple star systems[1], it is of interest to consider the existence of planets in such an environment. Searches for extrasolar planets using the radial velocity technique have shown that giant planets exist in certain types of multiple star systems (see Table 1 for further details). The number of such planets is, however, still low, in part because close binaries are difficult targets for radial velocity surveys and were consequently often rejected from the samples. Due to the limitations of the available observational techniques, most detected objects are giant (Jupiter-like) planets; the existence of smaller mass planets in multiple star systems is thus still an open question.

The orbital characteristics and the mass distribution of extrasolar planets can give us an insight into their formation mechanisms and their subsequent evolution. In the first paper of this series, Udry et al. (2003b; Paper I) discussed the period distribution and the mass-period diagram for extrasolar planets orbiting single stars. As pointed out by Zucker & Mazeh (2002), planets orbiting a component of a multiple star system seem to have different characteristics than planets orbiting single stars. Zucker & Mazeh (2002) showed that there is a significant correlation in the mass-period diagram for planets orbiting single stars, while there may be an anticorrelation in this same diagram for planets found in multiple star systems. The difference is mainly due to a paucity of massive planets with short periods, and to the fact that the most massive short-period planets are all found in binaries.

The characteristics of extrasolar giant planets have forced considerable modifications of the standard model of planet formation. It is now usually believed that planets form within a protoplanetary disc of gas and dust orbiting a central star, but the precise modes by which this formation takes place are still debated, especially for giant planets (e.g. Pollack et al. 1996; Boss 1997, 2000, 2003; Bodenheimer et al. 2000; Wuchterl et al. 2000). Two major models have been proposed to explain giant planet formation (see Sect. 4.3), each with its advantages and limitations, but there is currently no consistent model that accounts for all the observed characteristics of extrasolar planets. Observational constraints are thus needed, not only to specify our understanding of planet formation and evolution, but also to possibly discriminate between the proposed models. In this context, the detection and the characterization of planets orbiting in multiple star systems, even if more difficult to carry out than the study of planets orbiting isolated stars, may bring new constraints and additional information.

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[1] In this paper, double and multiple star systems will be called multiple star systems.

Table 1. Planets orbiting a component of a multiple star system with confirmed orbital or common proper motion (CPM stands for common proper motion and SB for spectroscopic binary).

Star	a_b (AU)	a_p (AU)	$M_p \sin i$ (M_J)	e_p	Notes	References
HD 40979	~6400	0.811	3.32	0.23	CPM[a]	12, 11
Gl 777 A	~3000	4.8	1.33	0.48	CPM	1, 23
HD 80606	~1200	0.469	3.90	0.927	CPM	22
55 Cnc	~1065	0.115	0.84	0.02	CPM	8, 21, 19, 2
		0.24	0.21	0.34		
		5.9	4.05	0.16		
16 Cyg B	~850	1.6	1.5	0.634	CPM	24, 5, 15
Ups And	~750	0.059	0.71	0.034	CPM	17, 24, 2, 3
		0.83	2.11	0.18		
		2.50	4.61	0.44		
HD 178911 B	~640	0.32	6.292	0.1243	CPM	28, 30
HD 219542 B	~288	0.46	0.30	0.32	CPM	7
Tau Boo	~240	0.05	4.08	0.018	orbit	13, 24, 2
HD 195019	~150	0.14	3.51	0.03	CPM	24, 1, 10
HD 114762	~130	0.35	11.03	0.34	CPM	24, 16, 18
HD 19994	~100	1.54	1.78	0.33	orbit	13, 25, 20
HD 41004 A	~23	1.33	2.5	0.39	SB	29, 31, 27
γ Cep	~22	2.03	1.59	0.2	SB	4, 6, 14
Gl 86	~20	0.11	4.0	0.046	CPM, SB[b]	9, 26

Notes: [a] According to Halbwachs (1986), this pair has only a probability of 60% to be physical. The physical nature of this binary has however been confirmed later on the basis of CORAVEL radial velocity measurements (Halbwachs, private communication); [b] The multiplicity status of this system has still to be clarified.

References: (1) Allen et al. (2000), (2) Butler et al. (1997), (3) Butler et al. (1999), (4) Campbell et al. (1988), (5) Cochran et al. (1997), (6) Cochran et al. (2002), (7) Desidera et al. (2003), (8) Duquennoy & Mayor (1991), (9) Els et al. (2001), (10) Fischer et al. (1999), (11) Fischer et al. (2003), (12) Halbwachs (1986), (13) Hale (1994), (14) Hatzes et al. (2003), (15) Hauser & Marcy (1999), (16) Latham et al. (1989), (17) Lowrance et al. (2002), (18) Marcy et al. (1999), (19) Marcy et al. (2002), (20) Mayor et al. (2004), (21) McGrath et al. (2002), (22) Naef et al. (2001), (23) Naef et al. (2003), (24) Patience et al. (2002), (25) Queloz et al. (2000a), (26) Queloz et al. (2000b), (27) Santos et al. (2002), (28) Tokovinin et al. (2000), (29) Udry et al. (2003a), (30) Zucker et al. (2002), (31) Zucker et al. (2003).

This paper is organized as follows. The sample of planets found in multiple star systems is presented in Sect. 2. Some trends seen in the statistics are then emphasized in Sect. 3. Models of formation and evolution of giant planets in binaries are briefly reviewed in Sect. 4 and their predictions are compared to the observations in Sect. 5. Our conclusions are drawn in Sect. 6.

2. Known planets in multiple star systems

Among the extrasolar planets discovered to date, some of them are orbiting a component of a multiple star system. Planets have been found around stars known to be part of a wide common proper motion pair, known to be in a visual binary or in a spectroscopic binary. Alternatively, searches for faint companions to stars hosting planets have revealed a few new systems. These observations, summarized in Table 1, show that giant planets can form and survive in certain types of multiple star systems.

3. Statistics of planets in multiple star systems

Although the sample of planets found in multiple star systems is not large, a preliminary comparison between the characteristics of these planets and the ones of planets orbiting isolated stars can be made. Here, we will discuss the mass-period and the eccentricity-period diagrams for extrasolar planets, focusing on possible differences between the two populations. Our sample of planetary candidates orbiting a component of a multiple star system consists of all the systems listed in Table 1. The total sample of extrasolar planetary candidates is made of 115 objects[2] with a minimum mass $M_2 \sin i \leq 18\ M_J$. The orbital elements used for the analysis are the ones deduced from our radial velocity data or the most recent version of the ones given in the literature.

3.1. The mass-period diagram

Figure 1 shows the distribution of all the extrasolar planetary candidates in the $M_2 \sin i$–$\log P$ plane. Two interesting features emerge from this plot: there are no short-period extrasolar planets with a mass $M_2 \sin i \gtrsim 5\ M_J$, and the most massive short-period planets are almost all found in multiple star systems (Udry et al. 2002; Zucker & Mazeh 2002; Paper I). Indeed, planetary candidates with a mass $M_2 \sin i \gtrsim 2\ M_J$ and a period $P \lesssim 40$ days are all orbiting a component of a multiple star system, the only exception being HD 162020 b. As explained in Udry et al. (2002), HD 162020 b is probably a brown dwarf with a true mass much larger than its minimum mass,

[2] See e.g. http://obswww.unige.ch/Exoplanets/

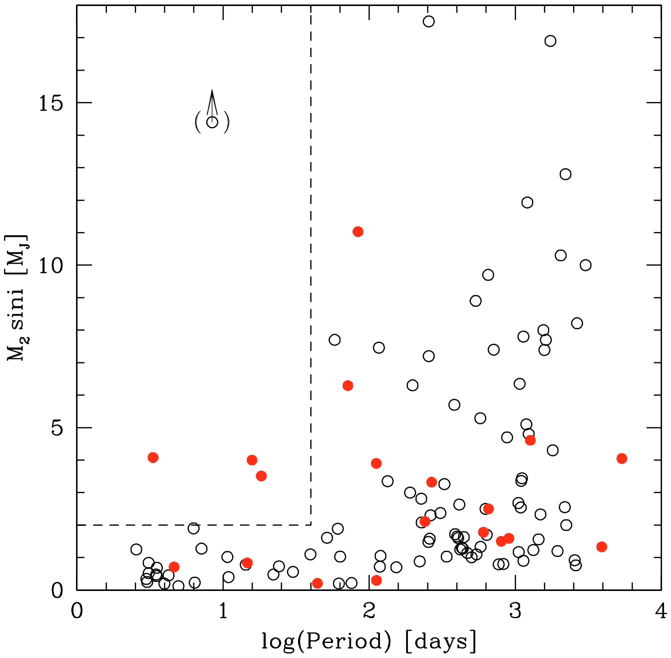

Fig. 1. Planetary minimum mass versus orbital period for the known extrasolar planetary candidates. Planets orbiting a single star are represented by open circles, while planets orbiting a component of a multiple star system are represented by filled circles. The dashed line approximately delimits the zone where only extrasolar planets belonging to multiple star systems are found.

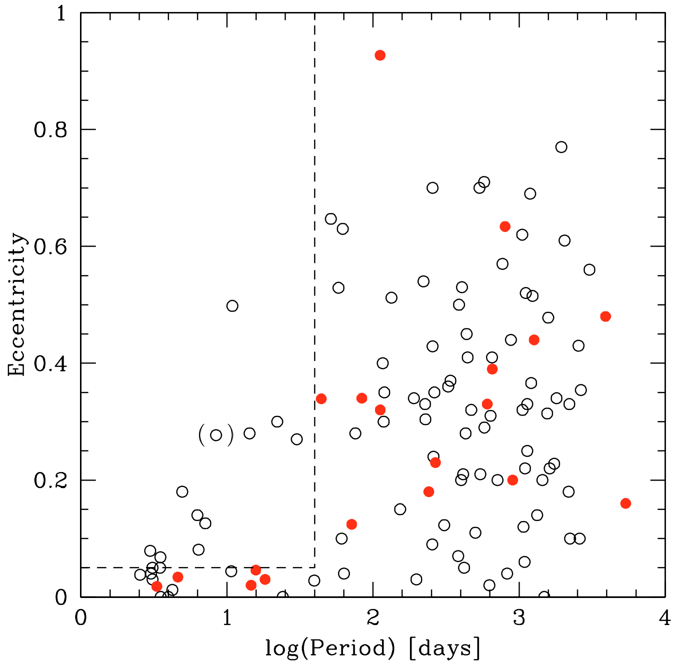

Fig. 2. Eccentricity versus orbital period for all the extrasolar planetary candidates. Same symbol coding as in Fig. 1. The dashed line approximately delimits the zone where there are no planets belonging to multiple star systems.

and should therefore be removed from our diagram. If it is true that no planet with a mass $M_2 \sin i \gtrsim 2\ M_\mathrm{J}$ orbiting a single star has been found with a period $P \lesssim 40$ days, the two populations of planets are somewhat mixed together for periods between 40 and 150 days. The orbital period below which there is no more massive planet orbiting a single star is thus not well defined, and such a unique and well defined limit may, in fact, not exist.

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 incomplete, the presence of a few candidates in a zone of the diagram where there are no other planets is significant. We will come back to these differences in Sect. 5.

For periods longer than ~100 days, the distribution of the planetary companions in the $M_2 \sin i$–$\log P$ plane is not very different for the two samples. In this period range, the mean mass of planets found in multiple star systems is, nevertheless, smaller than the mean mass of planets orbiting single stars. This difference comes from the fact that no very massive planet has been found on a long-period orbit around a component of a multiple star system. Again, this cannot be attributed to observational selection effects, because several planets with a smaller mass and on long-period orbits have been found in multiple star systems.

The lack of planets with $M_2 \sin i \geq 5\ M_\mathrm{J}$ and $P \geq 100$ days in multiple star systems can, however, be due to the small number of planets found in multiple star systems. To check this point, we computed the probability that, drawing a random subsample of 10 planets (i.e. the number of long-period planets found in multiple star systems when selection effects are taken into account) with $P \geq 100$ days out of the total population of planets with $P \geq 100$ days, we would have no planet with $M_2 \sin i \geq 5\ M_\mathrm{J}$ (see Appendix A.1 for further details). Using the hypergeometric distribution (Appendix A), this probability is 3.25% (selection effects have been taken into account by discarding from the counts the planets with a radial velocity semiamplitude $K < 15$ ms^{-1}). Thus, if the planets with $P \geq 100$ days orbiting in multiple star systems have the same properties as the planets with $P \geq 100$ days orbiting single stars, the probability not to have a single planet with $P \geq 100$ days and $M_2 \sin i \geq 5\ M_\mathrm{J}$ among our sample of planets found in multiple star systems is 3.25%. This result shows that this trend could be real. It is, however, not possible to exclude with a high confidence level that the lack of planets with $M_2 \sin i \geq 5\ M_\mathrm{J}$ and $P \geq 100$ days may solely be due to small-number statistics and that planets with $P \geq 100$ days orbiting in multiple star systems and around isolated stars may, in fact, belong to the same population. A larger sample of long-period planets orbiting in multiple star systems will be required to settle this question.

3.2. The eccentricity-period diagram

The distribution of the extrasolar planetary candidates in the e–$\log P$ plane is illustrated in Fig. 2. 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 star that tidal dissipation in the planet could have circularized their orbit, even if they were originally eccentric (Rasio et al. 1996). For longer periods, the orbits are not necessarily circularized anymore 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 by invoking tidal dissipation alone.

The hypergeometric distribution (Appendix A) was again used to test if the difference observed in this diagram may solely be due to the small size of the sample of short-period planets found in multiple star systems. In this case, we computed the probability to have 5 planets with $\log P \leq 1.6$ and $e < 0.05$ in a subsample of 5 planets with $\log P \leq 1.6$ drawn out of the total population of planets with $\log P \leq 1.6$ (see Appendix A.2 for more details). When selection effects are taken into account (by discarding from the counts the planets with a radial velocity semiamplitude $K < 15$ ms^{-1}), this probability is 3.77%. This means that the probability to have 5 planets with $\log P \leq 1.6$ and $e < 0.05$ in the sample of short-period planets orbiting in multiple star systems is 3.77% if these planets have the same properties as short-period planets orbiting isolated stars. On the basis of the current samples, there is thus a trend towards a difference in the properties of short-period planets orbiting in multiple star systems and around isolated stars. The alternative statement, namely that short-period planets orbiting in multiple star systems and around isolated stars belong to the same population can, nevertheless, not be excluded. The observation that the three extrasolar planets with periods between 10 and 40 days orbiting a component of a multiple star system have very low eccentricities is interesting and could be a clue to their formation and/or subsequent evolution history. We will come back to this point in Sect. 5.

For periods longer than ~40 days, there is no significant difference between planets found in multiple star systems and around isolated stars. The mean eccentricity is similar for the two samples.

3.3. Remarks

The limit at ~40 days is valid for both the eccentricity-period and the mass-period diagrams, but in the latter the limiting period is less well defined. If we plot the evolution of the mean mass or the highest mass (averaged on the three highest values) of planets orbiting single stars as a function of the period (see Fig. 6 of Paper I), there is a jump at a period of ~40 days, which reflects the distribution of these planets in the mass-period diagram. Thus, about the same limiting period is obtained by considering the distribution of planets orbiting single stars in the mass-period diagram on the one hand, and by considering the distribution of planets orbiting in multiple star systems in the eccentricity-period diagram on the other hand. This is intriguing.

Even if the orbital parameters of the binaries hosting planets are not exactly known, the projected separations of these systems (see Table 1) indicate that the five planets with a period shorter that 40 days reside in very different types of systems. There is thus no obvious correlation between the properties of these planets and the known orbital characteristics of the binaries or the star masses.

The history of planets found in multiple planet systems is probably different from the one of "single" planets. For the analysis presented here, all planets have been considered, but we have checked that our conclusions remain unchanged if the planets belonging to multiple planet systems are removed from the samples. Among the five short-period planets found in multiple star systems, two also belong to multiple planet systems. This is something that we must keep in mind when discussing the properties of these planets.

4. Models of formation and evolution of giant planets in binaries

Let us now turn to planet formation models and consider their predictions regarding the existence and the survival of giant planets in binary star systems. We will then be in position to compare and confront our observations with their results.

There are different points to take into account when considering the formation of giant planets in binaries. Indeed, the stellar companion affects all the stages of planet formation as well as the subsequent evolution of the planet once it has formed. The major points that have been studied in the literature are briefly described in this section.

4.1. Binary-disc interactions

Binary stars can in principle interact with three types of discs: two circumstellar and one circumbinary. Transfer of angular momentum between the binary and the disc leads to a truncation of the inner/outer edge for a circumbinary/circumstellar disc, respectively.

Artymowicz & Lubow (1994) investigated the approximate sizes of discs as a function of binary mass ratio and eccentricity for systems with circumstellar and circumbinary gaseous discs. Their results show that for a binary with a mass parameter $\mu = M_2/(M_1 + M_2) = 0.3$, the inner edge of a circumbinary disc is typically located at $r_t = 2.0\,a_b$ (where a_b is the binary semimajor axis) for nearly circular binaries and at $r_t = 3.0\,a_b$ for $e_b = 0.5$. The outer edge of a circumprimary disc lies at $r_t = 0.4\,a_b$ for nearly circular binaries and at $r_t = 0.18\,a_b$ for $e_b = 0.5$. For a circumsecondary disc, the outer truncation radius is located near $r_t = 0.27\,a_b$ for nearly circular binaries and near $r_t = 0.15\,a_b$ for $e_b = 0.4$.

4.2. Long-term stability of orbits

Assuming that planets can form in binary stars, do long-term stability regions exist for planetary orbits in these systems? Holman & Wiegert (1999) studied the long-time survival of planets in different regions of phase space near a binary star system. Circumprimary as well as circumbinary planets were studied for different values of the binary eccentricity and mass ratio. For a binary with a mass parameter $\mu = 0.3$, the largest stable orbit around the primary star has a critical semimajor axis $r_c = 0.37\,a_b$ for $e_b = 0.0$ or $r_c = 0.14\,a_b$ for $e_b = 0.5$. For the same binary, the smallest circumbinary orbit has a critical semimajor axis $r_c = 2.3\,a_b$ for $e_b = 0.0$ or $r_c = 3.9\,a_b$ for $e_b = 0.5$.

The study of Holman & Wiegert (1999) was restricted to planets in initially circular motion. Pilat-Lohinger & Dvorak (2002) extended this type of analysis and determined the variation of the stable zone due to an increase of the initial planet eccentricity. An increase of the planet eccentricity reduces the stable zone, this reduction being of course less pronounced that the one due to the same increase of the binary eccentricity.

As shown by Holman & Wiegert (1999) a companion star orbiting beyond about 5 times the planetary distance is not a serious threat to the long-term stability of planetary orbits. Nevertheless, this result only applies to orbits with a low mutual inclination. Innanen et al. (1997) investigated the stability of planetary orbits in binary systems with emphasis on the inclination of the orbital planes. As an example, they studied the stability of the solar system under the presence of an hypothetical distant companion placed at 400 AU with different inclinations and masses. Due to the Kozai mechanism (Kozai 1962), the system is unstable at high inclination when the companion mass is larger than 0.05 $M_\odot$. A low-mass companion does, however, not destabilize the system, even when the inclination is high.

4.3. Giant planet formation in binaries

Two mechanisms have been proposed to explain giant planet formation: core accretion and disc instability (e.g. Pollack et al. 1996; Boss 1997; Mayer et al. 2002). The core accretion mechanism begins with the collisional accumulation of planetesimals and planetary embryos in a protoplanetary disc, as for terrestrial planet formation. In the outer parts of the disc, where the amount of solid material is increased by the presence of ices, embryos may reach about 10 $M_\oplus$ in $\sim 10^6$ years and begin to grow an atmosphere of disc gas to form giant planets like Jupiter and Saturn in $\sim 10^7$ years. In the disc instability model, a gravitationally unstable disc fragments directly into self-gravitating clumps of gas and dust that can contract and become giant gaseous protoplanets. Coagulation and sedimentation of dust grains to the protoplanet center could form a solid core. This process occurs over a dynamical time scale: clump formation and dust grain sedimentation proceed nearly simultaneously in $\sim 10^3$ years. Though they are different, these two mechanisms share a common characteristic: giant planets should only form in the relatively cool outer regions of protoplanetary discs.

Boss (1998) considered the influence of a binary companion on giant planet formation via disc instability. 3D hydrodynamical models of discs with 0.04 $M_\odot$ were evolved in time, subject to the gravity of a binary star companion placed on a circular orbit at 40 AU. In the absence of the binary companion, the disc is stable, but in the presence of the binary companion the disc forms a multi-Jupiter-mass protoplanet in 0.002 Myr.

The evolution of two stars, each orbited by a circumstellar disc, was simulated by Nelson (2000) using a two dimensional smoothed particle hydrodynamic code. Each component of the binary had a mass of 0.5 $M_\odot$ and a binary eccentricity of 0.3 was considered. The system was evolved over 2700 yr (8 binary orbits). During and after periastron each disc developed strong two-armed spiral structures which decayed to a smooth condition over the next half binary period; this cycle repeating with little variations. The spiral structures decay was due to internal heating in the discs, which increased their stability against spiral arm growth. Giant planet formation via gravitational collapse is therefore unlikely in this system. In fact, the temperatures in the discs are so high, that some grain species, including water ices, are vaporized everywhere. Giant planet formation by the core accretion mechanism is thus unlikely as well in this system.

4.4. Evolution of an embedded planet in a binary

A different approach was considered by Kley (2001) who studied the evolution of a giant planet still embedded in a protoplanetary disc around the primary component of a binary system. A 1 M_J planet was placed on a circular orbit at 5.2 AU from a 1 $M_\odot$ star. The secondary star had a mass of 0.5 $M_\odot$ and an eccentricity of 0.5. The binary semimajor axis was varied from 50 to 100 AU. The simulations show that the companion alters the evolutionary properties of the planet: the mass accretion rate is increased and the inward migration time is reduced.

4.5. Summary

The main effect a companion has on a protoplanetary disc is a truncation of its radius and an induction of waves which, upon dissipation, transfer angular momentum between the binary and the disc. Comparing the results presented in Sects. 4.1 and 4.2, we see that a planet can almost always persists for a long time, wherever it forms in a truncated protoplanetary disc. The effect a secondary star has on the efficiency of planet formation is, however, less clear. According to Nelson (2000), the companion has a negative influence, slowing or inhibiting altogether giant planet formation. Boss (1998) claims the opposite, namely that giant planet formation via gravitational collapse is favoured in binaries. More comprehensive studies will be needed, not only to clear up the case of binaries with a separation of 40 or 50 AU, but also to explore what happens for binaries with different projected separations, mass ratios and eccentricities. Anyway, we expect the secondary star to have an influence on planet formation, at least for close binaries, and Kley (2001) has shown that this remains true for the subsequent evolution of giant planets in binaries. Planets found in multiple stars systems may thus have different characteristics than planets orbiting isolated stars.

5. Discussion

As mentioned in Sect. 4.3, in situ formation is very unlikely for short-period Jupiter-mass planets. Formation at larger distances followed by inward migration seems to be a better explanation to the existence of these planets (e.g. Lin et al. 1996; Bodenheimer et al. 2000). The high masses and low eccentricities of short-period planets orbiting in multiple star systems (Sect. 2 and Figs. 1 and 2) seem also to indicate that some kind of migration has been at work in the history of these systems. A few different migration mechanisms have been proposed to explain the existence and the characteristics of short-period giant planets. We will now briefly discuss two of them and see if they might explain some of the features emphasized in Sect. 2.

5.1. Planet-viscous disc interaction

One proposed migration mechanism involves the gravitational interaction of a protoplanet with the gaseous disc out of which it formed (Goldreich & Tremaine 1979, 1980; Ward 1986, 1997). Subject to such an interaction, high mass planets will migrate more slowly than low mass planets in a given disc because they create larger gaps. Moreover, some of these planets will experience mass loss as they come close to the central star. In overall, we thus expect to find more massive planets at intermediate and large semimajor axes, the population of close-in objects being dominated by smaller mass planets (Trilling et al. 2002). This is indeed observed (Paper I) and Zucker & Mazeh (2002) have shown that this effect is statistically significant.

Now, if we consider the evolution of a protoplanet orbiting the primary star of a binary system, we have seen that the presence of the companion alters the evolutionary properties of the planet, in particular the migration and mass growth rates are enhanced (Kley 2001). These differences may explain why the most massive short-period planets are found in multiple star systems: either they are more massive because of the higher mass accretion rate, or they are massive planets like the ones found with periods longer than ~100 days around single stars, but orbiting closer-in in multiple star systems because of the higher migration rate. Both of these effects are in fact probably mixed together and present at the same time.

Still regarding migration via the gravitational interaction of a Jupiter-mass protoplanet with a gaseous disc, models indicate that a realistic upper limit for the masses of closely orbiting giant planets is $\sim 5\ M_J$, if they originate in protoplanetary discs similar to the minimum-mass solar nebula (Nelson et al. 2000). Examples of large ($>5\ M_J$) planets at small orbital distances can, however, be obtained due to migration in discs with different masses or viscosities (Trilling et al. 1998). If such an upper mass limit exists for short-period planets, and if the scenario proposed by Kley (2001) is correct, we would expect to find an upper mass limit for short-period planets orbiting in multiple star systems that is larger than the one valid for planets orbiting single stars. Therefore, there should exist a zone in the mass-period diagram where only planets orbiting in multiple star systems are found, the presence of a stellar companion being the reason that enables a planet to reach a small separation with a mass larger than the limit corresponding to planets orbiting isolated stars.

In the simulations by Kley (2001), the planet eccentricity is also modified: it first grows due to the perturbations induced by the secondary star, but then declines because of the damping action of the disc. The final result is a rapid decay of the planet semimajor axis and a damping of the initial eccentricity.

Taken at face value, these arguments may provide an explanation for the observation that the most massive short-period planets are all found in multiple star systems and have very small eccentricities. It should, however, be noticed that several of the multiple star systems known to host planets are probably very different from the ones studied by Kley (2001). The five planets with a period shorter than 40 days orbit in binaries with very different separations (from ~20 to ~1000 AU) and it seems not likely 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.

5.2. Kozai migration

Another mechanism that may be at work in wide binaries is the so-called Kozai migration (Wu 2003; Wu & Murray 2003). In such a case, the Kozai mechanism (Kozai 1962; see also Holman et al. 1997; Innanen et al. 1997; Mazeh et al. 1997) produces large cyclic oscillations of the planet eccentricity. During the periods of high eccentricity, the periastron is small and, consequently, tidal dissipation becomes important and gradually removes energy from the planetary orbit, eventually leading to circularization. The Kozai mechanism coupled with tidal dissipation is thus a viable method by which a planet can migrate towards the central star.

Tidal dissipation depends sensitively on the nearest approach distance and is important only if the planet can reach a high eccentricity. As the eccentricity oscillations only depend on the inclination of the planet orbital plane relative to the binary orbital plane, the initial inclination between these two planes is a key parameter. Moreover, for the Kozai mechanism to be effective, the companion must provide the dominant contribution to the apsidal precession of the planet (see Holman et al. 1997 and Wu & Murray 2003 for more details). The efficiency of the Kozai migration is, however, fairly independent of the planet mass, and this mechanism will work for planets of relatively large masses (Wu 2003).

Although the Kozai mechanism may be efficient in binaries with large semimajor axes, several requirements must be simultaneously satisfied for it to operate, and such a mechanism will not apply to a large fraction of planetary systems. Furthermore, even if the Kozai migration has been efficient during a period in the evolution of a planet, it does not imply that its orbit is now circular. Up to now, the Kozai mechanism and the Kozai migration have been considered to explain the high eccentricity of given planetary candidates such as 16 Cyg B b and HD 80606 b (Holman et al. 1997; Mazeh et al. 1997; Wu & Murray 2003). It has never been demonstrated that the combination of the Kozai mechanism with tidal dissipation may account for the existence of close-in planets with very low eccentricities. On the other hand, Kozai oscillations are not likely to be currently at work for the planets with short semimajor axes, in particular because the Kozai mechanism is suppressed by general relativistic effects. It is thus very unlikely that the low eccentricity of these planets may be due to the fact that they are currently seen in their low-eccentricity phase. It seems therefore difficult to explain the characteristics of all the short-period planets orbiting in multiple stars systems by invoking the Kozai migration alone.

6. Conclusion

The characteristics of giant planets found in multiple star systems seem to be different from the ones of planets orbiting single stars, at least for the short-period planets. The major differences are:

- the most massive ($M_2 \sin i \gtrsim 2\ M_{\rm J}$) short-period planets all orbit in multiple star systems;
- the planets found in multiple star systems tend to have a very low eccentricity when their period is shorter than 40 days.

These observations seem to indicate that migration has played an important role in the history of the short-period planets orbiting in multiple star systems and that migration may be induced differently in binaries than around single stars.

From the theoretical point of view, it has been shown (Kley 2001) that the presence of a companion star affects the properties of a Jupiter-mass planet still embedded in a disc around the primary component of a binary by increasing the migration and mass accretion rates. Alternatively, the Kozai mechanism may be (or have been) at work in binaries hosting planets and will modify some of the orbital parameters of the planet. This mechanism can be efficient in wide binaries and, coupled with tidal dissipation, it may also lead to inward migration. Even if these two mechanisms may be invoked to explain the characteristics of a few planets orbiting in binaries, none of them seem to be able to account for all the properties of the five planets orbiting in multiple stars systems with a period $P \lesssim 40$ days. Nonetheless, it is also possible that diverse mechanisms may have been at work in these systems, but leading to a similar final state and similar planet properties. New studies dedicated to this issue will be needed to settle this question and to find a satisfactory explanation to the existence and the characteristics of the short-period planets found in multiple star systems.

From the observational point of view, a larger sample of planets orbiting in multiple star systems will be required to confirm or refute the preliminary trends emphasized in this paper. In this context, the search for planets in multiple star systems, even if more difficult to carry out than the search for planets around single stars is of importance. On the other hand, the characterization of the star systems susceptible of hosting planets is underway and could bring interesting constraints for the models, thus helping our understanding of giant planet formation.

Appendix A: The hypergeometric distribution

The hypergeometric distribution models the total number of successes in a fixed size sample drawn without replacement from a finite population of N items of which G are labelled *success* and $(N - G)$ are labelled *failure*. The hypergeometric distribution is described by three parameters: N, the size of the population; G, the total number of items with the desired characteristics in the population; and n, the size of the random sample drawn from the population.

The probability distribution of the hypergeometric random variable X, the number of successes in a random sample of size n selected from the total population is:

$$P(X = x) = \frac{C_x^G C_{n-x}^{N-G}}{C_n^N}$$

where $x = \max(0, n - (N - G)), \ldots, \min(n, G)$. This probability formula represents the ratio of the number of samples containing x successes and $(n - x)$ failures to the total number of possible samples of size n.

To test the statistical significance of the possible difference observed in the mass-period or in the eccentricity-period diagram, we considered a subsample of planets drawn from the total population of extrasolar planets (i.e. planets found in multiple star systems and around isolated stars). A planet was labelled *success* if it was located within the test zone of the diagram considered and *failure* otherwise. We then computed the probability that such a random subsample would give rise to a similar configuration as the one actually observed for planets found in multiple star systems, namely a configuration with the same number of planets within the test zone.

A.1. The mass-period diagram

We give here more details regarding the statistical significance of the lack of planets with $M_2 \sin i \geq 5\ M_{\rm J}$ and $P \geq 100$ days orbiting in multiple star systems (Fig. 1 and Sect. 3.1). As explained in Sect. 3.1, the hypergeometric distribution was used to compute the statistical significance of the difference observed. The parameters used were: $N = 77$, the number of planets with $P \geq 100$ days and $K \geq 15.0$ ms^{-1}; $G = 21$, the number of planets with $P \geq 100$ days, $M_2 \sin i \geq 5\ M_{\rm J}$ and $K \geq 15.0$ ms^{-1}; $n = 10$, the number of planets with $P \geq 100$ days and $K \geq 15.0$ ms^{-1} found in multiple star systems; and $x = 0$, the number of planets with $P \geq 100$ days, $K \geq 15.0$ ms^{-1} and $M_2 \sin i \geq 5\ M_{\rm J}$ found in multiple star systems. Given these parameters, we obtain a probability $P(X = 0) = 3.25\%$ to have no planet with $P \geq 100$ days, $K \geq 15.0$ ms^{-1} and $M_2 \sin i \geq 5\ M_{\rm J}$ among a subsample of 10 planets drawn from the total population of planets.

A.2. The eccentricity-period diagram

More details concerning the statistical significance of the possible difference observed for short-period planets in the eccentricity-period diagram (Fig. 2 and Sect. 3.2) are given here. The parameters used to compute the hypergeometric probability were: $N = 25$, the number of planets with $\log P \leq 1.6$ and $K \geq 15.0$ ms^{-1}; $G = 14$, the number of planets with $\log P \leq 1.6$, $K \geq 15.0$ ms^{-1} and $e < 0.05$; $n = 5$, the number of planets with $\log P \leq 1.6$ and $K \geq 15.0$ ms^{-1} orbiting in multiple star systems; and $x = 5$, the number of planets with $\log P \leq 1.6$, $K \geq 15.0$ ms^{-1} and $e < 0.05$ found in multiple star systems. The probability to have 5 planets with $\log P \leq 1.6$, $K \geq 15.0$ ms^{-1} and $e < 0.05$ in a subsample of 5 planets drawn from the total population of planets is then $P(X = 5) = 3.77\%$.

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References

Allen, C., Poveda, A., & Herrera, M. A. 2000, A&A, 356, 529
Artymowicz, P., & Lubow, S. H. 1994, ApJ, 421, 651
Bodenheimer, P., Hubickyj, O., & Lissauer, J. J. 2000, Icarus, 143, 2
Boss, A. P. 1997, Science, 276, 1836
Boss, A. P. 1998, AAS/Division for Planetary Sciences Meeting, 30, 1057
Boss, A. P. 2000, Earth Moon and Planets, 81, 19
Boss, A. P. 2003, in Planetary systems and planets in systems, ed. S. Udry, W. Benz, & R. Vonsteiger, Space Science Ser. ISSI (Kluwer Academic Publishers), in press
Butler, R. P., Marcy, G. W., Fischer, D. A., et al. 1999, ApJ, 526, 916
Butler, R. P., Marcy, G. W., Williams, E., Hauser, H., & Shirts, P. 1997, ApJ, 474, L115
Campbell, B., Walker, G. A. H., & Yang, S. 1988, ApJ, 331, 902
Cochran, W. D., Hatzes, A. P., Butler, R. P., & Marcy, G. W. 1997, ApJ, 483, 457
Cochran, W. D., Hatzes, A. P., Endl, M., et al. 2002, AAS/Division for Planetary Sciences Meeting, 34, 916
Desidera, S., Gratton, R. G., Endl, M., et al. 2003, A&A, 405, 207
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Eggenberger, A., Halbwachs, J., Udry, S., & Mayor, M. 2003, in The environments and evolution of double and multiple stars, Rev. Mex. Astron. Astrofis., in press
Els, S. G., Sterzik, M. F., Marchis, F., et al. 2001, A&A, 370, L1
Fischer, D. A., Marcy, G. W., Butler, R. P., Vogt, S. S., & Apps, K. 1999, PASP, 111, 50
Fischer, D. A., Marcy, G. W., Butler, R. P., et al. 2003, ApJ, 586, 1394
Goldreich, P., & Tremaine, S. 1979, ApJ, 233, 857
Goldreich, P., & Tremaine, S. 1980, ApJ, 241, 425
Halbwachs, J. L. 1986, A&AS, 66, 131
Hale, A. 1994, AJ, 107, 306
Hatzes, A., Cochran, W. D., Endl, M., et al. 2003, ApJ, 599, 1383
Hauser, H. M., & Marcy, G. W. 1999, PASP, 111, 321
Holman, M., Touma, J., & Tremaine, S. 1997, Nature, 386, 254
Holman, M. J., & Wiegert, P. A. 1999, AJ, 117, 621
Innanen, K. A., Zheng, J. Q., Mikkola, S., & Valtonen, M. J. 1997, AJ, 113, 1915
Kley, W. 2001, IAU Symp., 200, 511
Kozai, Y. 1962, AJ, 67, 591
Latham, D. W., Stefanik, R. P., Mazeh, T., Mayor, M., & Burki, G. 1989, Nature, 339, 38
Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, Nature, 380, 606
Lowrance, P. J., Kirkpatrick, J. D., & Beichman, C. A. 2002, ApJ, 572, L79
Marcy, G. W., Butler, R. P., Fischer, D. A., et al. 2002, ApJ, 581, 1375
Marcy, G. W., Butler, R. P., Vogt, S. S., Fischer, D., & Liu, M. C. 1999, ApJ, 520, 239
Mayer, L., Quinn, T., Wadsley, J., & Stadel, J. 2002, Science, 298, 1756
Mayor, M., Udry, S., Naef, D., et al. 2004, A&A, 415, 391
Mazeh, T., Krymolowski, Y., & Rosenfeld, G. 1997, ApJ, 477, L103
McGrath, M. A., Nelan, E., Black, D. C., et al. 2002, ApJ, 564, L27
Naef, D., Latham, D. W., Mayor, M., et al. 2001, A&A, 375, L27
Naef, D., Mayor, M., Korzennik, S., et al. 2003, A&A, 410, 1051
Nelson, A. F. 2000, ApJ, 537, L65
Nelson, R. P., Papaloizou, J. C. B., Masset, F., & Kley, W. 2000, MNRAS, 318, 18
Patience, J., White, R. J., Ghez, A. M., et al. 2002, ApJ, 581, 654
Pilat-Lohinger, E., & Dvorak, R. 2002, Celest. Mech. Dyn. Astron., 82, 143
Pollack, J. B., Hubickyj, O., Bodenheimer, P., et al. 1996, Icarus, 124, 62
Queloz, D., Mayor, M., Naef, D., et al. 2000a, in Planetary Systems in the Universe: Observations, Formation and Evolution, IAU Symp. 202, ed. A. Penny, P. Artymowicz, A.-M. Lagrange, & S. Russell, ASP Conf. Ser., in press, also available at http://obswww.unige.ch/Preprints/Preprints/cine_art.html
Queloz, D., Mayor, M., Weber, L., et al. 2000b, A&A, 354, 99
Rasio, F. A., Tout, C. A., Lubow, S. H., & Livio, M. 1996, ApJ, 470, 1187
Santos, N. C., Mayor, M., Naef, D., et al. 2002, A&A, 392, 215
Tokovinin, A. A., Griffin, R. F., Balega, Y. Y., Pluzhnik, E. A., & Udry, S. 2000, Astron. Lett., 26, 116
Trilling, D. E., Benz, W., Guillot, T., et al. 1998, ApJ, 500, 428
Trilling, D. E., Lunine, J. I., & Benz, W. 2002, A&A, 394, 241
Udry, S., Eggenberger, A., Mayor, M., Mazeh, T., & Zucker, S. 2003a, in The environments and evolution of double and multiple stars, Rev. Mex. Astron. Astrofis., in press
Udry, S., Mayor, M., Naef, D., et al. 2002, A&A, 390, 267
Udry, S., Mayor, M., & Santos, N. C. 2003b, A&A, 407, 369 (Paper I)
Ward, W. R. 1986, Icarus, 67, 164
Ward, W. R. 1997, Icarus, 126, 261
Wu, Y. 2003, in Scientific Frontiers in Research on Extrasolar Planets, ed. D. Deming, & S. Seager, ASP Conf. Ser., 294, 213
Wu, Y., & Murray, N. 2003, ApJ, 589, 605
Wuchterl, G., Guillot, T., & Lissauer, J. J. 2000, Protostars and Planets IV, 1081
Zucker, S., & Mazeh, T. 2002, ApJ, 568, L113
Zucker, S., Naef, D., Latham, D. W., et al. 2002, ApJ, 568, 363
Zucker, S., et al. 2003, in preparation