On the origin of eccentricities among extrasolar planets

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ABSTRACT
Most observed extrasolar planets have masses similar to, but orbits very different from, the gas giants of our Solar system. Many are much closer to their parent stars than would have been expected and their orbits are often rather eccentric. We show that some of these planets might have formed in systems much like our Solar system, i.e. in systems where the gas giants were originally on orbits with a semimajor axis of several au, but where the masses of the gas giants were all rather similar. If such a system is perturbed by another star, strong planet–planet interactions follow, causing the ejection of several planets while leaving those remaining on much tighter and more eccentric orbits. The eccentricity distribution of these perturbed systems is very similar to that of the observed extrasolar planets with semimajor axis between 1 and 6 au.

Key words: stellar dynamics – celestial mechanics – binaries: general – planetary systems.

1 INTRODUCTION
Since their first discovery (Wolszczan & Frail 1992; Mayor & Queloz 1995), more than 300 extrasolar planets have been found. In Fig. 1, we plot the semimajor axes and eccentricities of the planets detected using the radial velocity method as of 2008 October (Butler et al. 2006; Schneider 2008; Tamuz et al. 2008). As can be seen from the figure, the spread in eccentricity and separation is very large. A majority of the detected extrasolar planets have masses similar to, or larger than, those of the gas giants in our Solar system. Most planet formation models predict that such massive planets can only form outside the so-called snow line (situated at 3 au around a solar-mass star Kokubo & Ida 1998), but as can be seen from Fig. 1, most of the detected exoplanets have orbits tighter than this value. Thus, the orbits of most of the observed exoplanets must have shrunk considerably since their formation. The most efficient mechanism behind this is widely believed to be disc migration (Lin, Bodenheimer & Richardson 1996). However, disc migration almost exclusively produces planets on circular orbits, which does not agree with observations. Thus, in order to explain the observed eccentricities an additional mechanism must be at work.

The most popular such mechanism is scatterings due to strong planet–planet interactions, which can explain the observed eccentricities. Several different models which reproduce the observed eccentricities very well have been suggested and most likely the observed sample is created from a combination of these and perhaps others. It may, for example, be that planets come very close to each other while undergoing migration in the disc (Moorhead & Adams 2005) or that the planetary orbits are kept stable by the disc and as it evaporates the system becomes unstable (Thommes et al. 2008). Another possibility is that many planetary systems are initially too tightly packed, leading to that they become unstable on a time-scale of millions to several hundred million years and undergo strong planet–planet interactions (Marzari & Weidenschilling 2002; Barnes & Quinna 2004; Ford, Lystad & Rasio 2005; Chatterjee et al. 2008; Juric & Tremaine 2008).

It is, however, also possible that strong planet–planet interactions are triggered in long-term stable planetary systems (like e.g. our own Solar system) by external perturbations. Two examples of such are nearby passing stars in young stellar clusters (Zakamska & Tremaine 2004; Adams et al. 2006; Malmberg et al. 2007b) and the effects of a stellar companion in a binary (see e.g. Holman, Touma & Tremaine 1997; Mazeh, Krymolowski & Rosenfeld 1997; Holman & Wiegert 1999; Fabrycky & Tremaine 2007; Wu, Murray & Ramsahai 2007). In the latter case, there are two distinctly different scenarios. If the planetary system formed in a primordial binary system, the orbits of the planets and the companion star are expected to be essentially coplanar. The evolution of such a system has been studied extensively in, for example, Marzari et al. (2005). If the planetary system instead formed around an originally single star, which was later exchanged into a binary in an encounter in a young stellar cluster, the orientation of the orbits of the planets is completely random with respect to the orbit of the companion star. The evolution of the system is then very different from the coplanar case (Takeda & Rasio 2005; Malmberg, Davies & Chambers 2007a; Marzari & Barbieri 2007).

In this Letter, we study how a companion star in a binary, which formed through an exchange encounter in a young stellar cluster, can affect Solar-system-like planetary systems. A Solar-system-like planetary system is defined by us as a planetary system in which the gas giants are on long-term stable orbits wider than 5 au. We compare the eccentricity distribution of the resulting systems with the eccentricity distribution of the observed extrasolar planets at the time of this Letter.

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only compare our results to the observed planets with semimajor axis greater than about 1 au and hence we simulations will essentially only contribute to the observed extrasolar planets. It is, however, clear that the planetary systems produced in our simulations will essentially only contribute to the observed extrasolar planets with semimajor axis greater than about 1 au and hence we only compare our results to the observed planets with $a > 1$ au.

According to Cumming (2004), the detection efficiency of planets using the radial velocity method decreases sharply with increasing eccentricity for planets with $e > 0.6$. This implies that the observed eccentricity distribution is not complete above an eccentricity of 0.6. However, according to Shen & Turner (2008) the decrease in detection efficiency is not as strong as that predicted by Cumming (2004) and hence the observed eccentricity distribution is a good reflection of the true eccentricity distribution. Nevertheless, in order to be certain that we avoid comparing our simulations to a biased sample we only consider here the planets in the shaded area of Fig. 1, hence those with semimajor axes between 1 and 6 au and with eccentricity less than 0.6. We have calculated the cumulative eccentricity distribution of this sample, and find it to be increasing approximately linearly between an eccentricity of 0 and 0.6.

2 SAMPLE SELECTION

We define planets at intermediate separations as those with semimajor axes in the range 1–6 au. The upper limit roughly coincides with the observational limit and is only a little larger than the semimajor axis of Jupiter in the Solar system. Hence, 6 au roughly corresponds to where we would expect to start finding planets in an unperturbed Solar-system-like planetary systems. From our simulations we find that it is very unlikely for planets to be scattered on to orbits tighter than about 1 au. This is not an exact limit, and we do see a few planets on even tighter orbits in our simulations. It is, however, clear that the planetary systems produced in our simulations will essentially only contribute to the observed extrasolar planets with semimajor axis greater than about 1 au and hence we only compare our results to the observed planets with $a > 1$ au.

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3 PLANETS IN BINARIES

In Fig. 1, we have identified the planets found in binaries (filled circles) from those found around single stars (crosses) (Desidera & Barbieri 2007; Tamuz et al. 2008). It is clear from the figure that there is no obvious difference in the eccentricity distribution for planets in binaries with respect to that of planets orbiting single stars for the planets in the shaded region. It is, however, evident that the four most eccentric systems are found to be in binaries. Since the number of systems is very low, it is however too early to say if this is a real effect, or just a coincidence.

Using a thorough statistical analysis of the observed sample of extrasolar planets, Desidera & Barbieri (2007) showed that there is no significant difference between the eccentricity distribution of planets in binaries and that of planets orbiting single stars below $e = 0.6$. Above $e = 0.6$, there is possibly a slight excess of highly eccentric planets for the planets in (wide) binaries, although the statistical significance of this finding is, due to the low number of systems, not rigorous. This is a very important result, since it leaves only two possibilities:

(i) planetary systems are not affected by the presence of a companion star in a binary, or
(ii) the perturbation from the companion star in a binary triggers the same mechanism as that which gives rise to the observed distribution of eccentricities for planets around single stars.

The separation of most observed planet-hosting binaries is between 100 and 1000 au and the companion mass is between 0.2 and 2.0 $M_\odot$ (Desidera & Barbieri 2007). If most of the binaries with $100 < a < 1000$ au are not primordial, but were instead formed in exchange encounters in young stellar clusters, the orientation of the orbital plane of the planets with respect to the orbital plane of the companion star is completely random (see e.g. Malmberg et al. 2007a). In that case, about 77 per cent of the systems will have an inclination between the orbits of the planets and the orbit of the companion star greater than 39.2°. In such systems, the so-called Kozai Mechanism (Kozai 1962) operates, making the orbits of the planets more eccentric. This can, depending on the initial configuration of the system, trigger strong planet–planet interactions. For example, the four giants in our Solar system would, if put inside a binary with properties similar to those observed for planet-hosting binaries, undergo a phase of strong planet–planet interactions within a few million years, assuming that the inclination of the companion star with respect to the planets is large enough (see fig. 2 in Malmberg et al. 2007b).

Strong planet–planet interactions leave almost no trace of the initial eccentricities of the planets and it is thus most likely the dominating process behind the observed eccentricities among planet in binaries. Hence, alternative (i) is not correct, leaving us with alternative (ii): the perturbation from the companion star in a binary triggers the same mechanism as that which give rise to the observed distribution of eccentricities for planets around single stars. This mechanism is most likely scatterings caused by strong planet–planet interactions. For planets which orbit stars that are currently single, the strong planet–planet interactions might have occurred because the planetary system in which they formed was intrinsically unstable (see discussion in Section 1). However, it may be that some of the observed extrasolar planets come from Solar-system-like planetary systems. These strong planet–planet interactions occurred because the host star suffered a close encounter with another star or was exchanged into a binary in an exchange encounter in a young stellar cluster.
Such exchange encounters between single stars and binary systems may, in fact, be rather common in young stellar clusters, in which most stars form. We define a singleton as a star which did not form in a binary, has never later spent time within a binary and has never suffered a close encounter with another star. Not all of the stars that are single today are singletons. N-body simulations show that as a lower bound between 5 and 10 per cent of the current single field-stars with a mass close to 1 M⊙ has previously either suffered a close encounter with another star or been part of a binary system (Malmberg et al. 2007b). From a statistical analysis of radial–velocity searches for extrasolar planets, it has been estimated that about 7 per cent of all solar-mass stars have planets on orbits tighter than 5 au (Marcy et al. 2005). Hence, external perturbations by other stars on Solar-system-like planetary systems could account for a significant fraction of the observed systems with separations between 1 and 6 au. It is, however, also possible that the contribution is very small, depending on, for example, how common Solar-system-like planetary systems are and how effective fly-bys are for triggering strong planet–planet interactions.

4 SIMULATIONS

We performed more than 500 simulations of several different planetary systems in binaries, using the publicly available MERCURY code (Chambers 1999; Chambers et al. 2002). All simulations were run for 10^8 yr. In all our simulations, we have closely monitored the energy and angular momentum conservation, and if it failed using the appropriate symplectic integration algorithm (hybrid or wide binary) included in MERCURY, we reran the simulation, using exactly the same initial conditions, but with a Burlish–Stoer algorithm. In the end we used the Burlish–Stoer method for the majority of our simulations, since in systems where many strong close encounters between planets occurred, the energy conservation using the symplectic algorithms was not good enough.

One would expect there to be a wide variety of planetary systems (Levison, Lissauer & Duncan 1998) but here we divide them into two different groups: hierarchical and democratic. We only consider Solar-system-like planetary systems, i.e. systems containing giant planets with separations of around 5 au or larger. A hierarchical system is dominated by its most massive planet; an example of this is our own Solar system. A democratic system on the other hand consists of several planets of roughly similar, but not necessarily equal, mass. Due to the current observational limits, we have not yet observed any multiple planet systems with planets outside 6 au, apart from our own Solar system. To simulate a democratic system, we used the four giant planets in the Solar system but set their masses equal to that of Jupiter. To check that this system is stable we performed several simulations of it around a single star and found no signs of any secular trends in the orbital elements of the planets. When placed in a binary, we call this system 4 Jupiters-In-Binary (4JIB). Within this system, the perturbation of the companion star leads to large eccentricities and thus strong interactions between the planets, typically resulting in the ejection of all but one planet within a few Myr, leaving the remaining planet on a tighter and more eccentric orbit (see Fig. 2).

The effect of the companion star on the planets is to slightly perturb the outer planet, leading to strong planet–planet interactions in the system. Whether this happens or not depends both on the properties of the planetary system and the companion star. We have kept the properties of the companion star constant in all the runs from which we generate eccentricity distributions below, with a_e = 300 au, m_e = 0.6 M⊙ and e_e = 0.3. These properties are representative of binaries formed in exchange encounters in young stellar clusters (see fig. 5 in Malmberg et al. 2007b). Furthermore, the orientation of the orbit of the companion star with respect to the orbits of the planets in such binaries is random, and thus we assume that the inclination of binaries produced in exchange encounters is isotropically distributed.

In order to investigate how the final eccentricity distribution is affected by changing the binary properties, we have also performed simulations of the system consisting of four Jupiter-mass planets in a binary, with several different values of the semimajor axis of the binary. These show that there are essentially only two outcomes. Either strong planet–planet interactions are induced, resulting in an eccentricity distribution like that of the 4JIB with a_e = 300 au or the system remains unperturbed, resulting in an eccentricity distribution like that of the 4I. The probability that strong planet–planet interactions will be induced in the four Jupiter system decreases with increasing binary semimajor axis. It is close to one for all inclinations up to a_e ∼ 800 au and reaches zero for 1000 < a_e < 1500 au, the exact value depending on the inclination of the companion star. When comparing with the observed eccentricity distribution, we can thus account for different binary properties by combining, for example, the 4I and the 4IB distribution. Changing the mass of the companion star is essentially equivalent to changing its semimajor axis, since it only changes the strength of the perturbation. Hence, we expect the same outcome to be true when varying the mass as when varying the semimajor axis.

In order to generate a distribution of eccentricities from our simulations, we ‘observe’ the eccentricities and semimajor axes of all the planets in each simulation at several random times. To avoid the initial strong planet–planet interaction phase, we only considered the second half of our simulations, i.e. the last 50 Myr. We then

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\begin{align*}
\text{(1)} & \quad a_e = 300\text{ au} \\
\text{(2)} & \quad m_e = 0.6M_\odot \\
\text{(3)} & \quad e_e = 0.3
\end{align*}
\]
discarded all the planets with semimajor axes smaller than 1 or larger than 6 au (the observational limit) and those with an eccentricity greater than 0.6.

5 RESULTS

We find that the democratic 4JIB system gives rise to a cumulative eccentricity distribution which goes roughly as $e^2$ up to 0.6. We have also performed the same set of simulations for a system where we instead set the mass of the four giants in the Solar system equal to that of Uranus. This system gives rise to a very similar eccentricity distribution. It is interesting to note that the eccentricity distribution of democratic systems is very similar to the thermal eccentricity distribution $[f(e) = e^2]$ found for wide stellar binaries (Heggie 1975). We conclude that democratic systems, in general, produce an excess of eccentric systems compared to the observed planets. To compare this result with hierarchical systems, we simulated the four giants in the Solar System in a Binary (SSIB) and calculated the resulting eccentricity distribution. We find that there is a large excess of low-eccentricity systems produced compared to the observed planets.

We have also calculated the evolution of eccentricity of a single planet, considering the same stellar binary as used earlier, using the semi-analytic formulae derived from the so-called Kozai mechanism (Kozai 1962; Innanen et al. 1997; Carruba et al. 2002). This system can be thought of as an extreme example of a hierarchical system. The resulting cumulative eccentricity distribution is very similar to that, which we found from our SSIB simulations (see also Takeda & Rasio 2005). Planetary systems containing four Jupiters around a single star (4J) give rise to a cumulative eccentricity distribution having an excess of low-eccentricity planets compared to observations. In Fig. 3, we plot the cumulative distributions of all the above-mentioned systems. None of them individually provides a good match with the observed distribution. The KS probability when comparing the 4JIB eccentricities with those of the observed planets is about 0.001 and when comparing the SSIB eccentricities to those of the observed planets the KS probability is essentially zero. Hence, the eccentricities of the planets in our 4JIB and SSIB samples are very different from the eccentricities of the observed extrasolar planets.

6 DISCUSSION

Since democratic systems in binaries produce an excess of eccentric systems compared to the observations and hierarchical systems produce an excess of low-eccentric systems, it seems plausible that a combination of the two can provide a reasonable match to the observations. We plot an example of such a combination in Fig. 4. In this particular case, 70 per cent of the planets come from the 4JIB systems, while the remaining 30 per cent are a mix of SSIB and single planet in binary systems. Comparing this sample of eccentricities with the observed sample using a KS test gives a probability of 0.15. This is much larger than the probability when using a pure sample of either democratic or hierarchical systems, and as can be seen in Fig. 4 the match is rather good. This fit is surprisingly good considering that we have simply taken planetary systems derived from our own Solar system. This does not suggest that all planetary systems formed are either purely democratic or purely hierarchical. However, if the contribution to the observed extrasolar planet sample from Solar-system-like planetary systems exchanged into (and sometimes out of) binaries traces the observed eccentricity distribution, the ‘average’ Solar-system-like planetary systems must be significantly more democratic than the four giants in the Solar system. Simulations of planetary formation shows that a wide variety of planetary systems are formed, as can, for example, be seen in the extensive catalogue of planetary systems produced in simulations by Levison et al. (1998). It is encouraging to note that a significant fraction of systems formed in such are, by our definition, democratic.
7 SUMMARY

Most stars form in some sort of cluster or association and hence so do most planetary systems. In such crowded places initially single stars may be exchanged in and out of binary systems and/or pass close to other stars. We have performed a large set of simulations of Solar-system-like planetary systems whose host star have been exchanged into a binary. Because the binary was formed in an exchange encounter, the orientation of the orbits of the planets with respect to the orbit of the companion star is completely random. This means that the so-called Kozai mechanism operates in many of the systems, causing strong planet–planet interactions to occur. These, in turn, lead to the ejection of one or more planets, leaving those remaining on tighter and more eccentric orbits. We find that democratic planetary systems (in which the gas giants all have rather similar masses) in binaries produce an excess of highly eccentric systems compared to the observed extrasolar planets while hierarchical planetary systems (like our own Solar system) in binaries produce an excess of low-eccentric systems. A combination of hierarchical and democratic systems in binaries does, however, provide a good match to the observed eccentricities of extrasolar planets.

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