The instability of planetary systems in binaries: how the Kozai mechanism leads to strong planet-planet interactions

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ABSTRACT

In this letter we consider the evolution of a planetary system around a star inside a wide binary. We simulate numerically the evolution of the planetary orbits for both co-planar and highly-inclined systems. We find that the Kozai mechanism operates in the latter case. This produces a highly eccentric outer planet whose orbit crosses those of some of the inner planets. Strong planet-planet interactions then follow resulting in the ejection of one or more planets. We note that planetary systems resembling our solar system, formed around single stars in stellar clusters may exchange into binaries and thus will be vulnerable to planet stripping. This process will reduce the number of solar-system like planetary systems, and may produce at least some of the observed extra-solar planets.

Key words: Celestial mechanics, Stellar dynamics; Binaries: general, Planetary systems

1 INTRODUCTION

Of the 200 known extrasolar planets (see for example Butler et al. 2006) around 40 (Desidera & Barbieri 2007) are in known binary systems, while the fraction with an unseen companion (eg. brown dwarf) may also be significant (see for example Burgasser 2006; Lutheran et al. 2007). A key question is how the presence of the companion affects the orbits of the planets and the stability of the system. Various effects must be considered; if the systems consists of one planet inside a tight binary, a close encounter between the planet and the companion can lead to the ejection of the planet (Holman & Wiegert 1999). In wider binaries, secular effects, which builds up over thousands of orbits are important. Holman & Wiegert (1999) derived limits on the values which the semi-major axis and eccentricity of a companion star can have, without causing large effects on the orbits of the planets. Furthermore, Marzari et al. (2005) analyzed the importance of planet-planet interactions in multi-planet systems with a co-planar companion star. If the companion star is highly inclined to the orbital plane of the planets, an effect called the Kozai Mechanism (Kozai 1962) becomes important. Its importance for single-planet systems has been analyzed in for example Takeda & Rasio (2003). Given that the solar system is stable, it is possible to derive limits on the properties (mass and distance) that a hypothetical companion star to the sun could have, without causing severe damage to the solar system (Innanen et al. 1997; Holman & Wiegert 1999). In this letter we extend these studies, considering in more detail the evolution of planetary systems resembling our own solar system, when placed inside a binary. Formation of planetary systems in binaries is possible and has been studied in for example Barbieri et al. (2002); Marzari & Scholl (2000); Thébault et al. (2004, 2006); Boss (2006); Quintana & Lis (2006). In this letter however, we only consider planet formation around single stars. The key idea here is to have such single stars exchange into binaries in young stellar clusters. In such three-body encounters, it is possible that the planetary system will be destroyed immediately, but a significant fraction will be unaffected, assuming that the final binary is wide (see for example Davies et al. 1994). If this star had a planetary system this would now be randomly oriented with respect to the companion star. It is the evolution of these system that we study in this letter. In section 2 we discuss the integrator used to perform the numerical simulations presented in this letter. Then we give an overview of the Kozai mechanism in section 3. We present the results of our numerical simulations in section 4 which show that planet-planet interactions can cause the disruption of planetary systems if inside an inclined binary. In section 5 we discuss the implications for...
extra-solar planets and the vulnerability of planetary systems resembling our solar system.

2 SIMULATIONS - THE MERCURY CODE

The numerical simulations in this paper were done using a modified version of the publicly available MERCURY code, which we have specifically adapted for integrating planetary systems in binary stars. The original MERCURY code is described in Chambers et al. (2002), and the modifications in our version are described in Chambers et al. (2002).

The original MERCURY package (Chambers 1999) can accurately integrate planetary systems, including the effects of close encounters between planets, very fast. The high performance is achieved because it intrinsically conserves the angular and linear momentum of the system. Integrators which have this feature, are said to be symplectic. Another property of them is that they do not show any long-term build up of energy error, as conventional integrators do, although they do exhibit high frequency energy oscillations. The original mercury package could not accurately simulate a planetary system which was inside a binary. A method for adapting the MERCURY package, to allow for this, was however presented in Chambers et al. (2002) and we have here implemented those changes.

3 THE KOZAI MECHANISM

The Kozai mechanism was first discussed in Kozai (1962). He analyzed how the orbits of inclined asteroids in the solar system were influenced by Jupiter. In this case, the mass of the asteroid is much smaller than the mass of Jupiter. This is also true if we instead take the example of a Jupiter size extra-solar planet and a companion star and thus the same analysis holds for extra-solar planets within wide and inclined binaries (Innanen et al. 1997) (though see Carruba et al. 2002, 2003 for a corrected version of the Kozai equations). The Kozai mechanism causes the eccentricity of the planet to vary periodically, if the orbits of the planet and the companion star are sufficiently inclined. It has been used to explain the high eccentricity of the planet around 16 Cygni B (Holman et al. 1997; Mazeh et al. 1997) and also for more general studies of the eccentricities of planets in binary systems (Haghighipour 2004; Takada & Rasio 2004). Its importance for more general three-body systems has also been discussed in Ford et al. (2000). Furthermore, Carruba et al. (2004) gives a detailed discussion and analysis of the Kozai mechanism and use it to explain the orbits of irregular satellites in the solar system.

Returning to the application of the Kozai mechanism in this letter, one observes that it is only significant if the initial inclination, $i_0$, between the orbits of the planet and the companion star is greater than 39.23° ($\sqrt{2}/5$), which hereafter will be referred to as the critical angle, $i_{crit}$. If this is the case, the inclination of the planet will oscillate between $i_{crit}$ and $i_0$ and one also observes that $\sqrt{1 - e^2 \cos^2(i)}$ is constant (Kozai 1962). It can thus be shown, that the maximum eccentricity, $e_{max}$, of the planets orbit is (Innanen et al. 1997):

$$e_{max} = \sqrt{1 - \frac{5}{3} \cos^2(i_0)}.$$  

where it is assumed that the planets initial eccentricity, $e_0$ is close to zero. This is a lower limit on $e_{max}$, since if $e_0$ is greater than 0, the maximum eccentricity will increase. Using equation 1 one can see that if for example $i_0 = 60^\circ$, the eccentricity will reach a maximum value of $e_{max} = 0.76$. It is important to note that the effects of the Kozai mechanism can be washed out. The effects of nonspherical stars (Soderhjelm 1980; Innanen et al. 1997), relativistic precession (Holman et al. 1997; Ford et al. 2000), and planet-planet interactions over long timescales (Innanen et al. 1997) can all decrease the eccentricity build-up. If the Kozai mechanism is to dominate over the planet-planet interactions, its timescale must be sufficiently short. This depends strongly on the semi-major axis of the companion star and the planet and thus, in order to see a large eccentricity build-up, the semi-major axis of the companion star must not be too large.

To illustrate the Kozai mechanism, we ran simulations with the MERCURY code with a Neptune mass planet on Neptune’s orbit ($e_0 = 0.0088$ and $a_0 = 30.07$ AU), orbiting a one solar mass star, with a companion star with semi-major axis $a_c = 300$ AU, eccentricity $e_c = 0.3$, inclination $i_c = 60^\circ$ and mass $M_c = 0.5 M_{\odot}$. The parameters of the companion star are chosen to be representative for the known companions to planet-hosting stars in the solar neighborhood (Desidera & Barbieri 2007).

We plot the evolution of the eccentricity of the planet in one of these runs in Fig. 1. As can be seen, its eccentricity $e_p$ oscillates, as predicted by the Kozai mechanism, with maximum amplitude $e_{max} = 0.77$. We can compare this to the theoretical value, given by equation 1 which gives that $e_{max}$
should be equal to 0.76. Furthermore, one can see that the initial build-up of eccentricity is slow and then accelerates. It can be shown (Linnell et al. 1997) that the time to reach the first eccentricity maximum scales as $T \propto a_p^{-3/2}$, where $a_p$ is the semi-major axis of the planet, under the assumption that the binary parameters and the planets eccentricity are kept constant. We can now compare the Kozai time-scales of for example Uranus and Neptune and find that it is about twice as long for Uranus as it is for Neptune. Thus, in a planetary system consisting of two or more planets, the eccentricity of the outer planet will reach its maximum when the eccentricity of the inner planets is still almost at its initial value. This is because the eccentricity stays at its original value for quite a long time until the growth starts, but once it does, it is very fast, as can be seen in Fig. 1.

Thus, if an extra-solar planetary-system is within a highly inclined and not too wide binary, the Kozai mechanism can lead to a very large increase in the eccentricity of the outer planet. When this occurs, the inner planets will still be almost unaffected by the companion star. If the inclination is high enough, the eccentricity of the outer planet will be large enough for the orbits of the two outer planets to cross and hence strong planet-planet encounters are likely to occur. It is however very important to note, that when the eccentricity of the outer planet is at its maximum, the inclination between it and the companion star is at its minimum. This also means that the outer planet is inclined to the rest of the planets. This decreases the likelihood of planet-planet interactions. The outcome is that it can take several Kozai cycles before the planets have strong encounters (which depends on the phasing of the planets). Once they occur, such strong encounters can lead to large changes in both the semi-major axis and the eccentricity of the planets, or even the ejection of one or two of them, as we show in the following section.

### 4 NUMERICAL SIMULATIONS - RESULTS

As shown in the previous section, the Kozai mechanism can lead to strong planet-planet interactions. We investigate this here numerically, by taking the four gas giants of our own solar system around a one solar mass star and evolve the system within a binary. In Fig. 2 we plot the results of such a run, where the system has a companion star with $m_c = 0.5 M_\odot$, $a_c = 300$ AU, $e_c = 0.3$ and $i_c = 60^\circ$.

As can be seen, there is an almost immediate build-up in the eccentricity of the outer planet, and after only about 3 million years the outermost planets have been ejected, due to strong planet-planet interactions. By looking at the history of the close encounters that the two outer planets in the run in Fig. 2 had, it is possible to better understand what happens.

Both of them have a series of close encounters with the other planets and themselves, which coincide with their periods of high eccentricity over the first million years of the run. After this, there is a large change in the semi-major axis of the outermost planet, which leads to even more strong encounters between all the planets. Both the outer planets are then ejected shortly after each other, at around $2.5 \times 10^6$ years, due to strong encounters with the innermost planet.

One can from the close encounter history clearly see that all the sudden changes in the orbital elements of the planets seen in Fig. 2 are solely due to close encounters with other planets.

It could be possible that the results seen in Fig. 2 are due to the initial phasing of the planets and that planetary systems normally are less sensitive. To test this, we performed 10 different realizations of the run in Fig. 2 where we varied the initial phasing of the planets. The results of these runs were similar to those of the run shown in Fig. 2. In all of the 10 runs performed, one or two outer planets in the system were ejected within $6 \times 10^6$ years. It is important to note, that in all the 10 runs, the companion star suffers no close encounter with any of the planets, hence the ejection of planets are not due to strong interactions between the planets and the star.

To further test our hypothesis that the instabilities seen in Fig. 2 are caused by the Kozai mechanism, through the increased eccentricity of the outer planet and the following planet-planet interactions, we then performed another set of 10 runs. These had the same initial conditions for the companion star as in Fig. 2 but with the initial inclination between the planets and the companion star equal to $10^\circ$. Hence, the initial inclination between the orbital plane of the binary and that of the planets is much less than the critical angle ($39.23^\circ$), and so the Kozai mechanism should not be active. In all the 10 runs (which lasted for $10^8$ years), there is no build-up of eccentricity for the outer planet and thus we see no strong planet-planet encounters, and no ejections, as is expected from the Kozai theory.

If it is only planet-planet interactions that cause the ejection of one or more planets in the runs we performed, the outcome should be similar if we remove the companion star once the eccentricity of the outer planet is high. To test this,
we removed the companion star at a time when the eccentricity is at its maximum in the 10 highly-inclined runs discussed above. As expected, we still see planet ejections within the same time-scales, although the strong planet-planet encounters that lead to the ejections are not the same, which is also expected.

We have also performed simulations, where we place the four giants in a very wide binary to see whether the Kozai mechanism could be observed. This should not be the case, since the Kozai timescale becomes very long in this case, and its effect should be suppressed by the precession of the planets due to planet-planet interactions (see also Innanen et al. 1997). We again used the giant planets of the solar system as our test object, and this time placed a companion star at 1000 AU on a nearly circular orbit with an inclination of 60°. The simulation showed that no secular evolution due to the effects of the companion star occurred during the 10^8 years that we ran the simulation for.

5 DISCUSSION

As we have seen, a planetary system can be strongly affected by the presence of a companion star, even if the semi-major axis of the companions orbit is large. However, this is only true if the initial inclination between the orbital planes of the planets and the companion star is larger than the critical angle, 39.23°. If we assume that all planetary systems that are in binaries also were formed in them, it would be unlikely to find systems with such a high mutual inclination. This is because one would expect the rotational axis of the stars to be aligned and hence the disk out of which the planets formed would be in the same plane as the companion star. However, if the planetary system is formed around a single star, which is later exchanged into a binary, the orientation of the planets orbital planes will be random. One can show, that for systems who have formed this way, 77% will have an initial inclination above 39.23° and hence be in the region where the Kozai mechanism can be important. To understand how important the Kozai mechanism is for extrasolar planets, it is thus necessary to know how often stars are exchanged into binaries (Portegies Zwart & McMillan 2003; Adams et al. 2006; Pfahl & Muterspaugh 2006). Stars are formed in groups. Thus, early on, stellar encounters will be frequent in such crowded environments. This means that it might be quite common for stars to be exchanged in and out of binaries. It is therefore interesting to study the fraction of single stars which have never been in a binary or even suffered a close encounter with another star. We term such stars singletons. The fraction of single stars has been calculated (Malmberg et al. 2007) and the results show that a substantial fraction of the stars are not singletons.

To understand how important such interactions between stars are for planetary systems, we need a criterion for when they can cause significant damage to them. In the case that the star is exchanged into a binary for several 10^8 years, a companion star can cause several planets to be ejected, via planet-planet interactions induced by the Kozai mechanism. In the example of the solar system, Neptune’s and Uranus orbits will cross if the inclination between the companion star and the plane of the planets is greater than 43°. This will be the case in 73% of the binary systems formed in stellar encounters. It is thus possible that planetary systems initially resembling our own solar system may more closely resemble the observed extra-solar planetary systems due to planet-planet scattering induced by the Kozai mechanism. This is true also for single stars with planetary systems, since these may have previously been in a binary and later exchanged out of it.

If it is common for young planetary systems to be stripped of one or more planets while they are in young stellar clusters, we should be able to observe some of these planets. It is interesting to note that free-floating planetary mass objects has been observed in dense stellar clusters (see for example Lucas & Roche 2000). These objects might be young planets which have been ejected from its host system, but may also have been formed in other ways (eg. Whitworth & Zinnecker 2004).

From the simulations which we have performed, we do not see the formation of so-called hot Jupiters. These are Jupiter mass planets found at very small distances (a few stellar radii) from the host star, on almost circular orbits. However, hot Jupiters may be formed from planets that have strong tidal encounters with the host star, which however requires that the planets have very eccentric orbits (Faber et al. 2006). If the inclination between the planets and the companion star is near 90° the Kozai mechanism will, in the absence of relativistic effects, cause such high eccentricities, if the binary is not too wide. Thus, it might be possible to explain hot Jupiters in this way. However, observations imply that at least some highly eccentric planetary systems have avoided tidal circulation (Wu & Murray 2003). We will return to this problem in a subsequent paper.

As we have seen above, no strong secular effects occur in our runs with planetary systems within a co-planar binary. This is true as long as the separation between the companion star and the central star is large. However, if the separation is smaller than 100 AU, one or more planets might be ejected from the system (Marzari et al. 2003). Here, we do not see any significant build-up of the planets eccentricities in the low inclination case. However, we do see a small increase in the mutual inclinations between the planets and their respective eccentricities.

6 SUMMARY

We have simulated the evolution of planetary systems, resembling our own solar system, inside wide binaries. We find, that if the inclination between the orbital plane of the companion star and the orbital planes of the planets is larger than 39.23°, the Kozai mechanism will lead to an increase in the eccentricity of the outer planet, if the binary is not too wide. The increased eccentricity of the outer planet leads to strong planet-planet interactions in the system, which can lead to the ejection of one or more planets and also that the remaining planets are left on more eccentric orbits than before. As stars are formed in groups, they will, during the first 100 million years after their birth, be in a crowded environment. This means that they can exchange into binaries in stellar encounters, with a random orientation of the orbital plane of the planets, with respect to the orbital plane of the companion star. Thus, a planetary system resembling our own solar system formed around a single star, is at risk of
exchanging into a binary and being stripped of one or more planets.

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