Induced Eccentricities of Extra Solar Planets by Distant Stellar Companions

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Abstract. This paper explores the assumption that the high eccentricities of the extra solar planets were induced by distant stellar companions. I put some constraints on possible, yet undetected, companions that could generate the observed eccentricities. Distant companions can also induce low eccentricities into the planetary orbits. The results of such an effect can be detected when low but significant eccentricities are measured for short period planets, for which we expect the orbit to have been circularized long ago. The feasibility of such an effect is briefly discussed.

1. Introduction

The relatively high eccentricities of some of the extra solar planets compose one of the surprising features of the newly discovered population (e.g., Schneider, 2003). Naively, one could expect low eccentricity orbits for planets that were formed out of a disk of particles that circle a central star in circular orbits (e.g., Kornet, Bodenheimer and Rozyczka, 2002), as indeed is the case for the planets in our Solar system.

Since the discovery of the planetary high eccentricities, various mechanisms have been proposed to explain their formation and/or dynamical evolution (e.g., Weidenschilling and Marzari, 1996; Chiang, Fischer and Thommes, 2002; Marzari and Weidenschilling 2002). One of these ideas was that the high eccentricities were induced by distant stellar companions. This idea was put forward immediately after Cochran et al. (1996) announced the discovery of a planet orbiting 16 Cyg B. The new planet had two special pronounced features. The first one was its high orbital eccentricity – $0.63 \pm 0.08$ (Cochran et al., 1997), which was remarkably larger than the eccentricities of all other seven planets known at that time. The other feature was the binarity of the parent star, which has a distant stellar companion – 16 Cyg A, at a separation of about 40 arc-sec (Hoffleit and Jaschek, 1982). Therefore, the suggestion that the two features are interrelated was a natural assumption. Three works (Mazeh, Krymolowski and Rosenfeld, 1997; Holman, Touma and Tremaine, 1997; Innanen et al., 1997) studied this effect for 16 Cyg B and showed that the high eccentricity could have been pumped by the distant companion.

Since the discovery of 16 Cyg Bb a few more planets with highly eccentric orbits were found, the most recent one being HD 80606 with an eccentricity of 0.93 (Naef et al., 2001). Not all those planets are known to have distant stellar companions. It seems therefore that even if we accept this model, we have to assume either that the parent stars of all eccentric planets have distant faint, yet
unknown, companions, or that in some cases there is another mechanism behind
the high eccentricities of the extra solar planets.

In this article I review briefly the dynamics of the pumping. Following the
work of Holman, Touma and Tremaine (1997) and Lin et al. (2000), I put some
constraints on the presumed distant companions that could induce the presently
known high eccentricities. A similar effect can be observed by detecting small but
significant eccentricity for planets with short periods, where we expect the orbit to
circularize to a high level. I discuss briefly the feasibility of such an effect.

2. The Eccentricity Modulation

Mazeh and Shaham (1979) have shown that in hierarchical stellar triple systems
the third distant star can modulate the inner binary eccentricity. This effect was
already pointed out by Kozai (1962), who studied the motion of some asteroids
under the gravitation of the Sun and Jupiter. Stellar triple systems are characterized
by mass ratios close to unity, whereas the typical mass ratio in the Sun-Jupiter-
asteroid system is 1:0.001:0. Nevertheless, the nature of the modulation is the same,
as shown by Harrington (1968) and Lidov and Ziglin (1976). A system with two
stellar components and a planet has a typical mass ratio of 1:1:0.001, in between
the stellar triple systems and the asteroids. As such, its modulation is of the same
nature.

Mazeh and Shaham (1979), using a second-order Hamiltonian of the three-
body problem (Harrington, 1968, 1969) estimated the modulation period of the
eccentricity for a stellar triple system to be

\[ P_{\text{mod}} \sim P_3 \left( \frac{P_3}{P_{1,2}} \right) \left( \frac{M}{m_3} \right), \]

(1)

where \( P_3 \) is the third star orbital period, \( P_{1,2} \) is the close binary period, \( M \) is the
total mass of the binary system, and \( m_3 \) is the mass of the distant companion. For
our case we get

\[ P_{\text{mod}} \sim P_{\text{bin}} \left( \frac{P_{\text{bin}}}{P_{\text{plnt}}} \right) \left( \frac{m_{\text{prim}}}{m_{\text{comp}}} \right), \]

(2)

where \( P_{\text{bin}} \) is the orbital period of the stellar binary system, \( P_{\text{plnt}} \) is the orbital period
of the planet, and \( m_{\text{prim}} \) and \( m_{\text{comp}} \) are the masses of the parent star of the planet and
its distant companion, respectively. For 16 Cyg B this formula yields a modulation
period of the order of \( 3 \times 10^8 \) y, or 100 million inner orbit revolutions. The model
assumes that 16 Cyg B is at present in one of its high eccentricity phases that lasts
for about 100 millions years.

The long period of the eccentricity modulation is due to the large semi-major
axes ratio of the 16 Cyg system, which renders the tidal forces of A exerted on B
and its planet very small. One might think that the weakness of the tidal force turns
the amplitude of the eccentricity modulation to be small. This intuition is wrong. It is true that the weakness of the tidal forces makes the eccentricity variation very slow. However, the total increase of the planetary eccentricity, being accumulated for a long period of time, can be substantial. The theory shows that in some cases an initial minute eccentricity can grow by the tidal forces of the distant star up to 0.8 and higher, with a modulation period of the order of 10–100 million years.

3. Two Types of Eccentricity Modulation

From the seminal work of Kozai (1962) we know that the modulation of the planetary eccentricity, \(e\), is associated with two other parameters of the planetary orbit – the longitude of the periastron, \(g\), and the inclination of the planetary orbit relative to the plane of motion of the distant companion, \(i\). Specifically:

\[
\frac{de}{dt} \propto e \sqrt{1 - e^2} \sin(2g) \sin^2 i .
\]  

(3)

Following Kozai we also know that to first order we have two constants of motion for the planetary modulation. The first is

\[
\Theta = \cos^2 i (1 - e^2) ,
\]  

(4)

which is proportional to the square of the angular momentum of the planetary motion. The second is the second-order Hamiltonian

\[
H_{2nd-order} = -[1 - 3 \cos^2 i](2 + 3e^2) + 15[1 - \cos^2 i]e^2 \cos(2g) .
\]  

(5)

These two constants make the motion such that one of the three variables – \(e\), \(i\), or \(g\), determines the other two. It is therefore possible to describe the variability of the system by a contour in a parameter space of any two of the three variables. Following Kozai, I present in Figs. 1 and 2 the variability of the planetary orbit in the \((e, \cos(2g))\) space. This is especially convenient, as the time derivative of the eccentricity is proportional to \(\sin(2g)\), and therefore the sign of \(\sin(2g)\) determines whether the eccentricity increases or decreases.

Figure 1 presents such contours for \(\Theta = 0.8\). The maximum inclination for this value of \(\Theta\) is 26.6°, which results in \(e = 0\). In this case the second-order derivative of \(e\) vanishes, and the orbit does not vary. (Note that the longitude of the periastron is not defined in such a case.) This case is presented in the figure by the upper horizontal boundary. For different values of \(e\), up to about 0.45, we get small eccentricity modulation, as depicted in Fig. 1. The lower boundary of the figure corresponds to an inclination of 0°, where the two planes of motions coincide, and the derivative of the eccentricity vanishes as well.

Kozai (1962) also showed that some systems can show two types of modulation, depending on the value of \(\Theta\). For \(\Theta\) smaller than 0.6, \(2g\) can librate, and the \(e\) modulation can be substantial. The two types of modulation are depicted in Fig. 2,
Figure 1. The eccentricity modulation for $\Theta = 0.8, \; x = 1 - e^2$

Figure 2. The eccentricity modulation for $\Theta = 0.2$
which is plotted for $\Theta = 0.2$. Some of the contours present libration of $2g$, which oscillates around $0^\circ$ without covering the whole range of angles.

A graph that shows the possible modulations of Cyg 16B is presented in Fig. 3 (Mazeh, Krimolowski and Rosenfeld, 1997). It shows the maximum possible eccentricity of the modulation as a function of the initial inclination, assuming the binary eccentricity is 0.85. To derive the eccentricity variation Mazeh, Krimolowski and Rosenfeld used their third-order expansion of the Hamiltonian, which agrees very well with numerical integration of Newton equations of the problem. The maximum eccentricity starts to grow when the inclination gets larger than $40^\circ$. This reflects the fact that for $\Theta$ smaller than 0.6 the $(e, \cos(2g))$ parameter space is separated into two regions, and some of the curves extend to high eccentricities, as presented in Fig. 2.
4. Suppression of the Eccentricity Modulation

As we have seen, the eccentricity modulation is controlled by the variation of the longitude of the periastron. The slow eccentricity variation can accumulate up to large values only because the longitude of the periastron itself varies on a long time scale. Therefore, any additional drive that pushes the longitude of the periastron into faster precession and shortens the periastron cycle suppresses the accumulation of the eccentricity modulation (Holman, Touma and Tremaine, 1997; Innanen et al., 1997; Lin et al., 2000). One such effect is the famous General Relativity (GR) precession of the periastron, with a period of

\[ P_{\text{GR}} = 3.36 \times 10^7 \, \text{y} (1 - e_{\text{plnt}}^2) \left( \frac{P_{\text{plnt}}}{1 \, \text{ly}} \right) \left( \frac{m_{\text{prim}}}{1 \, \text{M}_{\odot}} \right)^{-1} \]  \hspace{1cm} (6)

(Holman, Touma and Tremaine, 1997).

This timescale has to be compared with the period of the eccentricity modulation driven by a stellar companion given above, which will be written now as

\[ P_{\text{mod}} \sim P_{\text{plnt}} \left( \frac{m_{\text{prim}}}{m_{\text{comp}}} \right) \left( \frac{a_{\text{bin}}}{a_{\text{plnt}}} \right)^3 (1 - e_{\text{bin}}^2)^{3/2} \]  \hspace{1cm} (7)

where \( e_{\text{bin}} \) is the binary eccentricity (Holman, Touma and Tremaine, 1997).

The GR precession period can be derived from the known planetary parameters. Therefore, we can put upper limits on the distance of any possible companion that can strongly modulate the planetary eccentricity of each planet. This is done in Table 1, which lists all the known planets with eccentricity larger than 0.6, together with their \( P_{\text{GR}} \), which varies between 0.7 and 400 My. I consider two possible distant companions, one with mass of 0.1 \( M_{\odot} \) and eccentricity of 0.4, and another with mass of 0.4 \( M_{\odot} \) and eccentricity of 0.9. The Table lists the corresponding maximum distances of the two possible stellar companions, such that their modulation period would be about equal to \( P_{\text{GR}} \), so their effect would not be completely suppressed by the GR effect.

The maximum distances of the possible stellar companions range from 25 to 700 AU. Faint companions in this range of distances could have escaped detection. The last column of the Table lists the projected distances of the known companions to those planets. One can see that except for Cyg 16 B, the orbits of the known companions are much larger than the largest semi-major axes that could allow for eccentricity pumping. Therefore, the known secondaries could not have induced modulation that accounts for the present high eccentricity.
5. Small Planetary Eccentricity

An eccentricity modulation induced by a distant stellar companion does not necessarily have to be large. The discussion above has shown that if the relative inclination is smaller than 40°, the eccentricity modulation could be a few percent, as depicted in Fig. 1. In fact, we anticipate naively that the relative inclination would be small, especially if the binary and the planet have common origin. The results of such an effect can be observed by detecting small but significant eccentricity for planets with short periods, where we expect the orbit to circularize to a high level.

This effect can also be suppressed by the GR precession. Therefore, for the small eccentricity pumping to work we again need the GR time scale to be long enough. To see if this is plausible we consider a planet with an orbital period of the order of 10 days and a binary with a period of the order of 10 years. The ratio of the two precessions is

\[ \frac{P_{\text{GR}}}{P_{\text{mod}}} \sim 20 \left( \frac{P_{\text{plnt}}}{10 \text{ days}} \right)^{8/3} \left( \frac{P_{\text{bin}}}{10 \text{ y}} \right)^{-2} \left( \frac{m_{\text{prim}}}{1M_\odot} \right)^{-2/3} \left( \frac{m_{\text{comp}}}{m_{\text{prim}}} \right) \left( \frac{1 - e_{\text{plnt}}^2}{1 - e_{\text{bin}}^2} \right)^{3/2}. \]  

(8)

The effect can work as long as this ratio is not substantially smaller than unity. This implies that even if the companion mass is only 0.1 or even 0.05 of the primary mass, the effect can still work. Such a small companion is not easy to detect, either by radial velocity or astrometry, and a dedicated observational search for a possible faint companion is probably needed.

6. Discussion

This paper has shown that the GR effect puts strong constraints on the maximum distance of any possible stellar companion that could generate the present high...
eccentricity of the eccentric planets. Out of the four known planets that have both high eccentricity and detected stellar companion, only 16 Cyg A could have generated the eccentricity of 16 Cyg Bb. This does not prove that the effect does not work. We probably did not notice many of the faint stellar companions to nearby bright stars, because of the small angular separation and the large visual contrast. We can turn the argument around and use the values of Table 1 as a guide to an observational search for distant companions that caused the high eccentricity.

Another planet in the system can also suppress the eccentricity modulation induced by a distant companion. In such a system, the longitude of the periastron of each of the two planets will be modulated by the tidal forces of both the distant companion and the other planet, suppressing the eccentricity modulation. Furthermore, two planets in some configurations tend to get locked in apsidal resonance, in which the longitude of their periastra vary together (e.g., Lee and Peale, 2003; Beauge, Ferraz-Mello and Michtchenko, 2003). In such systems, the modulation of the distant companion will be minimal.

Small but significant eccentricity of a planetary orbit with short period is an intriguing feature. Such eccentricity was found in a few short period stellar binary systems (Mazeh, 1990; Jha et al. 2000; Mazeh et al., 2001; Tokovinin and Smekhov, 2002). Interestingly enough, a few planets with periods shorter than 4 days show indications for small eccentricities. One example is HD 179949, with a period of 3.09 days and eccentricity of 0.05 ± 0.03 (Tinney et al., 2001). Unfortunately, the finite eccentricity is still not highly significant. When better orbits are available for HD 179949 and similar planets, a search for possible faint companions would be of great interest.

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References

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