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EXOSYSTEMS IN KOZAI RESONANCE: HOW TO INCREASE THE MUTUAL INCLINATION?

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Abstract. We show that extrasolar two-planet systems, similar to the ones observed, are compatible with a stable Kozai-resonant state. Five known two-planet systems (not in mean motion resonance, MMR) are treated (υ Andromedae, HD 12661, HD 169830, HD 74156, HD 155358) here. We find that four of these systems have physical/orbital characteristics that are consistent with stable, Kozai-type, motion in 3-D, provided that their mutual inclination is at least $\sim 45°$. In order to address the formation of such systems, physical mechanisms that could produce large mutual inclinations have to be studied, such as (a) planet formation, (b) Type II migration and MMR interactions (gas-dominated phase), (c) planetesimal-driven migration (gas-free era), and (d) multi-planet scattering, caused by the presence of an additional planet. For the systems studied here, mechanism (d) seems to be the most promising scenario for pumping the mutual inclination and possibly establishing Kozai resonance.

1. INTRODUCTION

The discovery of about thirty extrasolar multi-planetary systems, whose planets have orbital characteristics quite different from the ones in our system, has opened new questions about the formation, evolution, and stability of such systems. Due to observational limitations, the spatial resolution of their orbits is currently impossible. Thus, numerical studies are employed, in order to analyze the stability of the detected systems, for different mutual inclinations. In some of these studies, the importance of the Kozai resonance on the long-term behavior of extrasolar systems has been noted. Indeed, the Kozai resonance offers a secular phase-protection mechanism, such that the system remains stable, even though both orbits may suffer large-scale variations both in eccentricity and inclination (see Kozai 1962). In Section 2, we show that a good fraction of two-planet exosystems may be compatible with stable, Kozai-resonant, motion in 3-D, under some conditions. Possible mechanisms that could produce such non-coplanar systems are then discussed (Section 3).

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Table 1: Parameters of Butler et al. (2006) for the exosystems analyzed in this work, except for those of HD 155358 released on the website http://exoplanet.eu/

	a_1 (AU)	a_2 (AU)	e_1	e_2	ω_1 (deg)	ω_2 (deg)	$m_1 \sin i_1$ (M_{Jup})	$m_2 \sin i_2$ (M_{Jup})
υ And	0.832	2.54	0.262	0.258	245.5	279	1.98	3.95
HD 12661	0.831	2.86	0.361	0.017	296.3	38	2.34	1.83
HD 169830	0.817	3.62	0.310	0.33	148	252	2.9	4.1
HD 74156	0.29	3.35	0.6360	0.583	181.5	242.4	1.8	6
HD 155358	0.628	1.224	0.112	0.176	162	279	0.89	0.504

2. EXTRASOLAR SYSTEMS IN KOZAI RESONANCE

The Kozai resonance was studied thoroughly in the analytical works of Michtchenko et al. (2006) and Libert and Henrard (2007). In the latter, a 12th order expansion in eccentricities and inclinations of the perturbing potential of the 3-D secular three-body problem was used to study the dynamics of the problem. The dynamical system can be reduced to a two degrees of freedom problem, by referring the planetary orbits to the Laplace plane (*elimination of the nodes*, see Jacobi 1842). The main concern of that work was to find the position and stability character of the equilibria, and show the generation of the stable Kozai equilibria through bifurcation from a central equilibrium, which itself becomes unstable at high mutual inclination (usually at $40° - 45°$). This implies that, around the stability islands of the Kozai resonance, an important zone of chaotic planetary motion exists.

In the Laplace plane, the Kozai-resonant regions are characterized by the coupled variation of the eccentricity and inclination of the inner planet and the libration of its pericentre argument about $\pm 90°$. In Libert and Tsiganis (2008), we showed that, for a general reference frame, such as the one formed by considering the plane of the sky as reference plane, the libration of this angle is not necessary for the system to be in Kozai resonance. As we concluded, the main characteristic that can be used to discriminate between a secular non-resonant behavior and a Kozai-resonant behavior is the coupling or non-coupling of the eccentricities of the two planets.

To examine the possibility that some of the detected exosystems can harbor Kozai-type motion in 3-D, a parametric study was undertaken for five two-planet systems that are not in mean motion resonance (υ Andromedae (b-c), HD 12661, HD 169830, HD 74156, HD 155358 - see Table 1 for their parameters) by varying the (unknown) inclinations of their orbital planes and their nodal longitudes (sky-plane reference frame), thus changing their masses and mutual inclination. We have chosen to vary both inclinations in sucha way as to keep the mass ratio constant. We have selected the nodes in such a way that the mutual inclination ($\cos I_{mut} = \cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos \Delta\Omega$) is in the range $[40° - 60°]$.

Four of the five selected systems (υ Andromedae, HD 12661, HD 169830, HD 74156) are consistent with a stable Kozai-resonant state for a large range of initial parameter values (80%), as their eccentricities and secular phases are such that the system would be placed inside the island of stable motion of the Kozai resonance, provided that their mutual inclination is at least 45°. Moreover. An exception is the υ And system, for

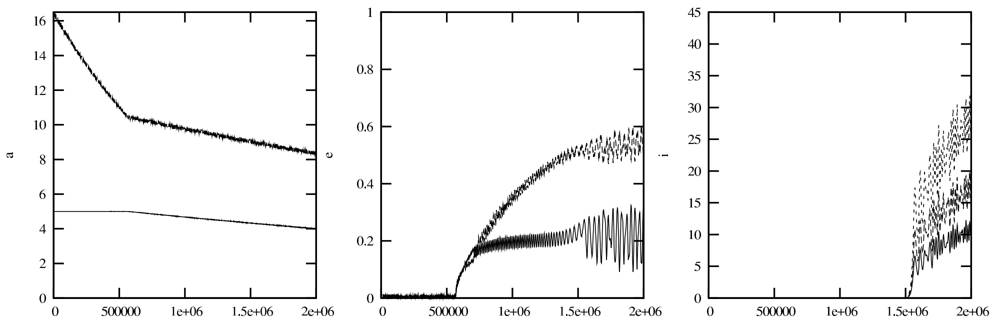

Figure 1: Example of 3/1 MMR interaction during Type II migration.

which only $30 - 50\%$ of our initial conditions lead to chaotic motion, related to the separatrix of the Kozai resonance. We refer to Libert and Tsiganis (2008) for more details.

It should be stressed that observational uncertainties and/or incomplete modeling from our part (e.g. the absence of general-relativistic precession) are such that one cannot identify candidate-systems for Kozai-type motion with the desired certainty. However, our study shows that a good fraction of the detected multi-planetary systems have physical/orbital characteristics compatible with 3-D Kozai-resonant state. Thus, we argue that, assuming mutual inclinations of $45° - 60°$, the probability for an exosystem to be in a Kozai-resonant state is significant. Given that, we discuss, in the following section, several formation mechanisms that could produce systems with the high mutual inclinations, as necessary for Kozai resonance.

3. FORMATION MECHANISMS

A first possible mechanism can act very early in the life of a planetary system, namely during the formation of the giant planet cores, by accretive collisions of smaller embryos. According to Levison et al. (1998), this violent dynamical process, characterized by orbital excitation, can form systems in secular or even Kozai resonance. On the other hand, this raises questions about how such non-coplanar, multi-planet, systems would behave in the presence of the protostellar gas nebula.

When the two-planet system is in the gas-dominated phase, Type II migration and resonant interactions can act together to pump the eccentricities and inclinations up to very high values, as shown by Thommes and Lissauer (2003), where this mechanism resulted into capture in the 2/1 MMR at high I_{mut}. Our preliminary results show that a similar effect can also be produced in the vicinity of the 3/1 MMR, in the case of slow inward migration of the outer planet (see Fig. 1). However, resonances of higher order, which are consistent with the semi-major axes ratios of the systems studied here, are completely inefficient in pumping either the eccentricities or the inclinations.

Once the disk is dissipated, planetesimal-driven migration and resonance crossing is another possible mechanism. This scenario has already proved itself very effective in the shaping of the orbits of the giant planets in our solar system (Tsiganis et

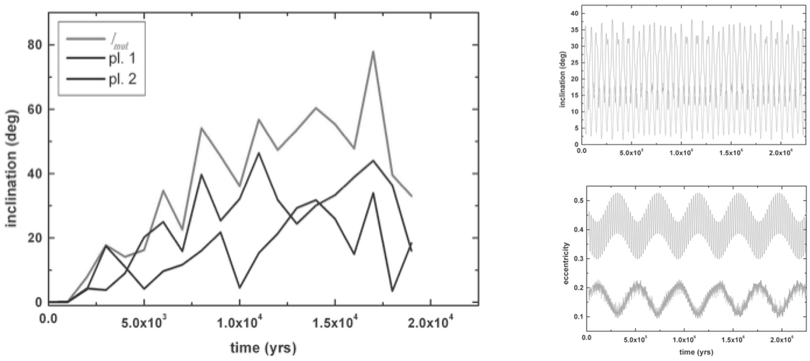

Figure 2: Example of 3-D multi-planet scattering.

al. 2005). Our numerical experiments have shown that, due to the large masses of the extrasolar planets ($2 - 4M_{Jup}$), a 'standard' planetesimals disc does not induce significant migration to such massive planets. Very high disc masses may work, but this assumption does not seem to be physically realistic.

Finally, a last mechanism is explored: multi-planet scattering caused by the presence of an additional planet in the system. This is the mechanism generally invoked to explain the large eccentricities observed in many exosystems (see e.g. Ford et al. (2005) who studied the 2-D case). Our first results show that 3-D scattering can also generate high mutual inclination values. An example of such an increase in I_{mut} is given in Fig. 2. Starting with $e \simeq 0.001$ and $I_{mut} \simeq 0.01$, planet-planet scattering leads to the increase of the mutual inclination of the two planets (gray curve - left panel of Fig. 2) and the escape of the third one from the system. Once the third planet is ejected, the remaining pair of planets is stable with high eccentricities and high mutual inclination (right panel of Fig. 2).

In conclusion, multi-planet scattering seems to be the most promising scenario for the formation of non-resonant, non-coplanar, systems, with $I_{mut} > 40°$. Of course, the correct astrophysical picture should also include a massive gaseous disc, in which the three planets may be driven to instability. To this end, a 3-D model of three planets trapped in multiple resonance due to Type II migration is under way.

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