Complex Planetary Systems
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Influence of the inclination damping on the formation of planetary systems

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Abstract. Highly non-coplanar extrasolar systems (e.g. Upsilon Andromedae) and unexpected spin-orbit misalignment of some exoplanets have been discovered. In Libert and Tsiganis (2011), a significant increase of the mutual inclination of some multi-planet systems has been observed during the type II migration, as a result of planet-planet scattering and/or resonant interactions between the planets. Here we investigate the effect of the inclination damping due to planet-disk interactions on the previous results, for a variety of planetary systems with different initial configurations and mass ratios. Using the damping formulae for eccentricity and inclination provided by the numerical hydrodynamical simulations of Bitsch *et al.* (2013), we examine their impact on the possible multiple resonances between the planets and how the growth in eccentricity and inclination is affected.

Keywords. planetary systems: formation, planet-disc interactions, resonance capture, inclination

1. Introduction

Planet-planet scattering and resonant planet-planet interactions during migration of giant planets in the protoplanetary disk have been invoked to explain the inclined orbits of extrasolar systems (Libert and Tsiganis (2011), Thommes and Lissauer (2003)). During the migration of the planets, the disk affects their eccentricity and inclination. While eccentricity damping is generally considered in the simulations, this is not the case for inclination damping. Bitsch *et al.* (2013) performed three-dimensional numerical hydrodynamical simulations of protoplanetary disks with embedded high-mass planets on fixed orbits and provided damping formulae for eccentricity and inclination that fit the numerical data. Using these formulae, we investigate here, for a variety of planetary systems with different initial configurations and mass ratios, the effect of the inclination damping on the possible multiple resonances between the planets and how the growth in eccentricity and inclination is affected.

2. Numerical set-up

We consider here two models for the protoplanetary disk. In the first case the mass of the disk is constant and there is no migration or eccentricity and inclination damping for the inner planet. The outer planets migrate with a constant rate depending on their initial semi-major axis (Ward (1997))

$$\tau_{II}(yr) = \frac{1}{9.4}\frac{1}{\alpha}\left(\frac{a}{H}\right)^2\left(\frac{a}{AU}\right)^{3/2}. \tag{2.1}$$

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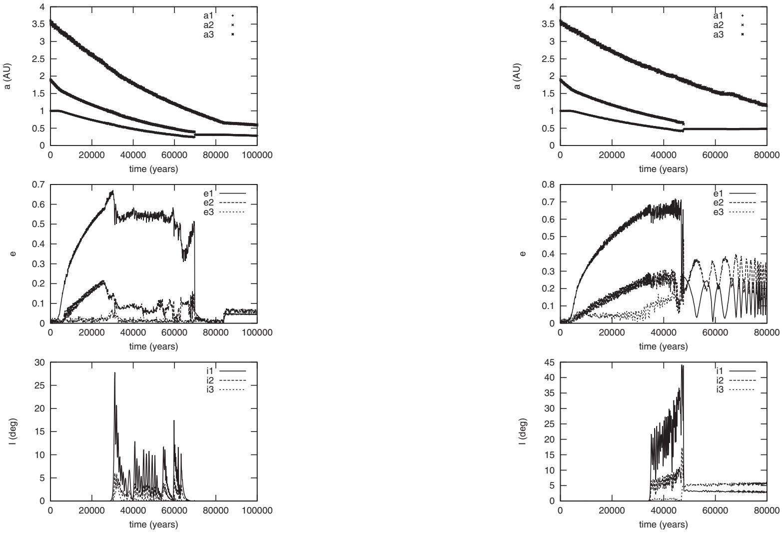

Figure 1. Left panel: A typical evolution of a three-planet system when considering inclination damping (constant mass of the disk). Right panel: Evolution of the same system without eccentricity and inclination damping, as shown in Libert and Tsiganis (2011).

In the second set of simulations, the mass of the disk is decreasing exponentially $M_{disk} = M_0 e^{-t/10^6}$ and the lifetime of the disk is $\sim 10^7$ yr. All the planets are initially affected by the protoplanetary disk and there is an inner cavity in the disk starting at 0.05 AU.

We have a total of 60 systems for each set of simulations. For both sets the initial parameters of the inner planet are $a_1 = 1$ AU and $m_1 = 1.5\ M_J$. For the outer planets, we consider the parameters: $a_2 = 1.9$ AU, $m_2 = 3, 1.5, 0.75\ M_J$, $a_3 = 2.8, 3, 1, 3.6$ AU and $m_3 = 6, 3, 1.5, 0.75, 0.375\ M_J$.

3. Results

The main observation of this preliminary work is that inclination damping has a strong impact on the evolution of the planets evolving in the gas disk, since non-coplanar systems are not a usual outcome any more. An example is given in Figure 1, where although the systems evolve in a Laplace three-body resonance, inclinations of the planets eventually tend to zero when considering the eccentricity and inclination damping of Bitsch *et al.* (2013).

In the first set of simulations, with a constant mass of the disk, the systems end-up with small mean values in eccentricity and inclination ($\bar{e} \sim 0.066, e_{max} = 0.2265, \bar{I} \sim 0.001°$), so planet-planet scattering and resonant interactions between the planets seem to be less efficient than in previous works.

However, in the second set of simulations, eccentricity and inclination excitations are observed due to the dissipation of the mass of the protoplanetary disk. Indeed, while in the Laplace resonance, mergings between the planets and ejections of one (or two) companions are usual outcomes and the final distribution of the systems is quite similar to the one of Libert and Tsiganis (2011). Final system configurations of a bigger set of simulations have to be further analyzed.

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