# Influence of the inclination damping on the formation of planetary systems

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## Motivation and context

**Aims.** Resonant planet-planet interactions during migration of giant planets in the protoplanetary disk have been invoked to explain the inclined orbits of extrasolar systems[1],[2]. 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.

**Methods.** We use the damping formulae for eccentricity and inclination provided by the numerical hydrodynamic simulations of Bitsch et al. (2013) [3] and we examine their impact on the possible multiple resonances between the planets and how the growth in eccentricity and inclination is affected.

## System configuration

**Two disk models:** *Initial mass disk* $M_0 = 10M_J$

1. In the first case we consider the mass of the disk as **constant** and no migration or eccentricity and inclination damping for the inner planet. The other 2 planets migrate with a constant rate depending on their initial semi-major axis (Ward's formula[4]).
2. In the second set of simulations, the mass of the disk is **decreasing** exponentially ($M_{disk} = M_0 e^{-t/10^6}$, $T_{disk} \sim 10^7$ 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 (no planet-disk interaction inside the cavity).

**Initial orbital configuration:** $a_1 = 1$AU, $m_1 = 1.5M_J$, $a_2 = 1.9$ AU, and we have considered the cases $a_3 = 2.8, 3.1, 3.6$ AU, $m_2 = 3, 1.5, 0.75M_J$ and $m_3 = 6, 3, 1.5, 0.75, 0.375M_J$, in total *27 systems* for each set.

## Effects of eccentricity and inclination damping on three-planet systems due to planet-disk interactions

### 1st set - The mass of the disk is constant $(10M_j)$ $(a_3 = 3.6AU, m_2 = 1.5M_J, m_3 = 0.75M_J)$

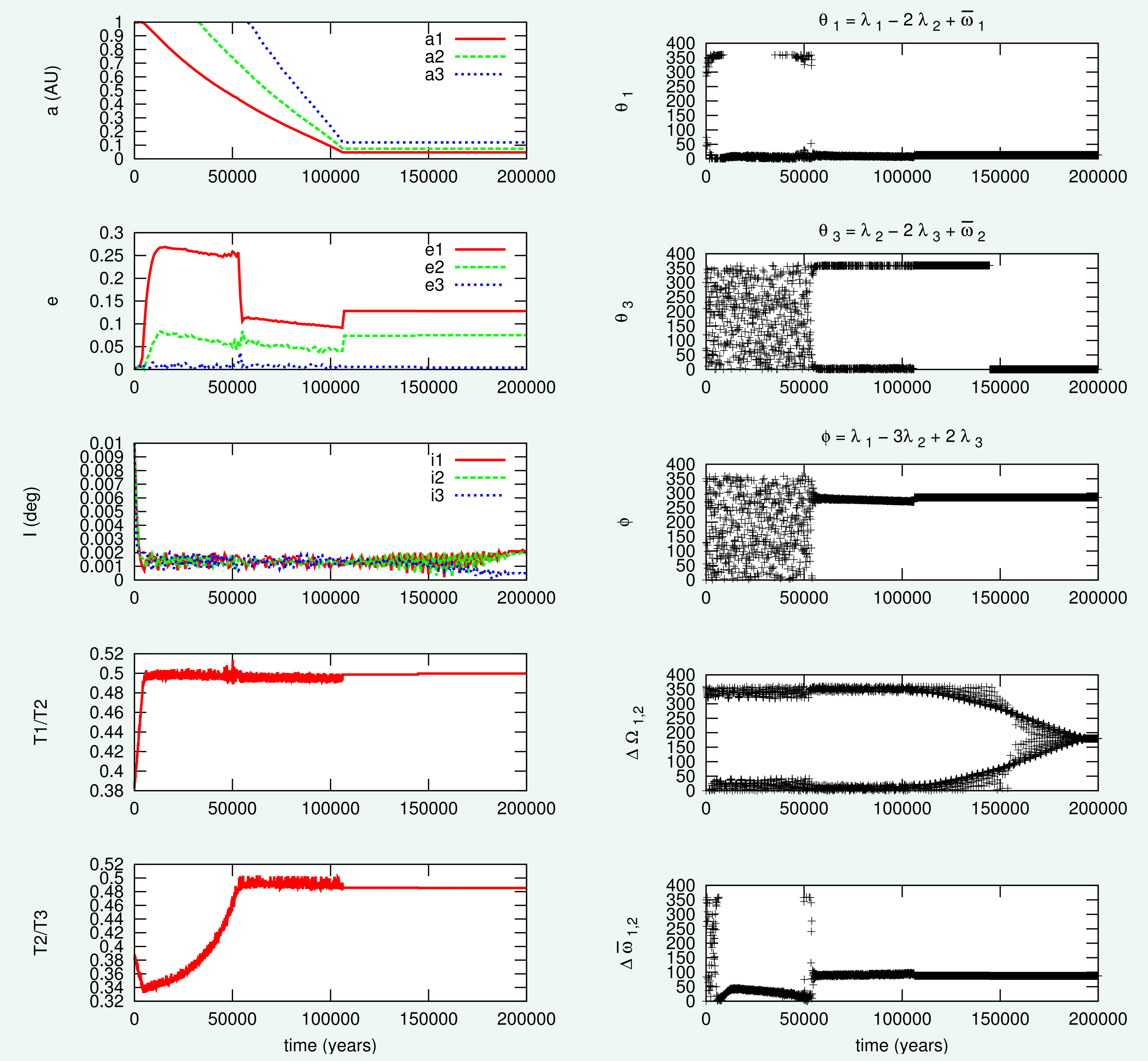


Figure 1 : Three-planet system in Laplace resonant configuration (1:2:4). The planets end-up in very compact configuration and the mutual inclinations between the planets remains near to zero.

### 2nd set - The mass of the disk is decreasing - inner disk boundary at 0.05AU. $(a_3 = 3.6AU, m_2 = 1.5M_J, m_3 = 1.5M_J)$

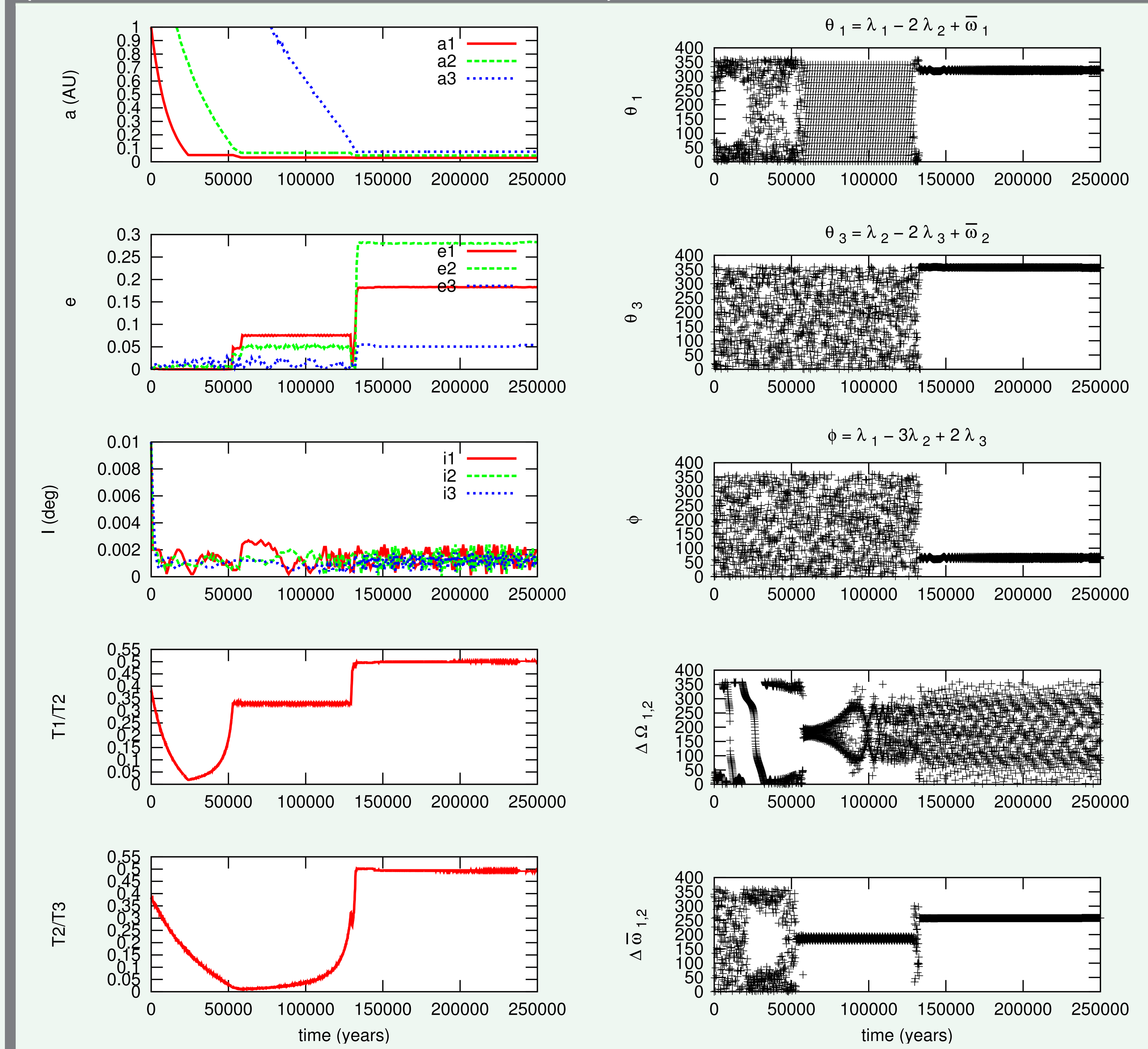


Figure 2 : A typical evolution for a system of the 2nd set. The two inner planets reach the 1:3 resonance, before the outer one comes close to establish a Laplace resonant configuration. As the system evolves, the eccentricities are excited due to the dissipation of the disk (figure 3).

RESULTS: When we include eccentricity and inclination damping:

Set 1:

- More stable: $\sim 62\%$ of the systems end-up in three-body MMR. Laplace resonance 1:2:4 is the usual outcome.
- Eccentricity and inclination values are small ($\bar{e} \sim 0.066, e_{max} = 0.2265, \bar{I} \sim 0$) and damping is more efficient than previously observed.

Set 2:

- Less stable: Merging and ejection are usual.
- Possible eccentricity and inclination excitation due to the dissipation of the mass of the disk (figure 3).

In conclusion: Strong impact of eccentricity and inclination damping and the mass of the disk on the evolution of the planets.

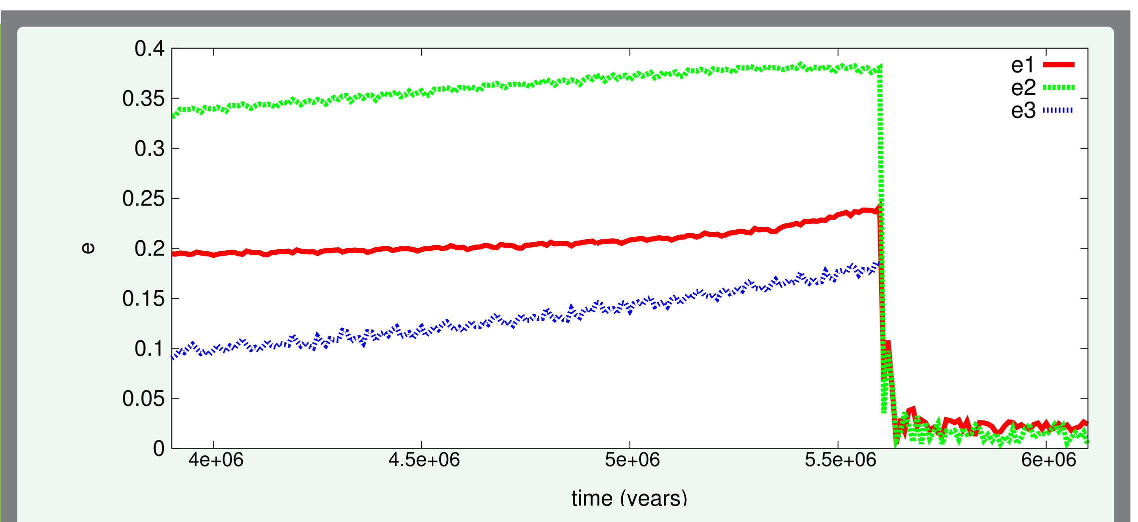


Figure 3 : The same system as in figure 2 but later in the integration. The system remains in the Laplace resonance, the eccentricities increase due to dispersion of the disk and finally a merging takes place.

FUTURE WORK:

- Simulations of $N > 1000$ systems with a variety of initial orbital configurations and different disk models to compare with the observed eccentricity and inclination distribution of extrasolar planets.
- Study of the resonant planet-planet mechanism and the possible impacts from inclination damping on that mechanism.

[1 ] A.-S. Libert, K. Tsiganis, *Trapping in three-planet resonances during gas-driven migration*, CeMDA, 111, 2011
[2 ] E.W. Thommes, J.J. Lissauer, *Resonant inclination excitation of migration giant planets*, ApJ, 597, 2003
[3 ] B. Bitsch, A. Crida, A.-S. Libert, E. Lega, *Highly inclined and eccentric massive planets I: Planet-disc interactions*, A&A, 555, 2013
[4 ] W.R. Ward, *Protoplanet migration by nebula tides*, Icarus, 126, 1997

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