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Formation of giant planetary systems: effect of the eccentricity and inclination damping

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Abstract

Observational evidence (e.g. strong spin-orbit misalignment) shows that a study of the efficiency of the disc-induced migration on the formation of non-coplanar systems is essential. We follow the orbital evolution of three giant planets in the late stage of the gas disc and investigate the influence of the eccentricity and inclination damping due to planet-disc interactions, on the final configurations of the systems. Our n-body simulations use the damping formulae for eccentricity and inclination provided by the numerical hydrodynamic simulations of Bitsch et al. (2013). We present the results of $\sim$10000 numerical experiments, exploring different initial configurations, planetary mass ratios and disc masses. Special attention is given to the multiple resonance captures during the migration of the planets and the subsequent growth in eccentricity and inclination. Our simulations correctly reproduce the observed eccentricity distribution except for low initial disc masses. We also show that a significant fraction of non-coplanar systems are formed, despite the strong inclination damping.

1. Introduction

Several mechanisms have been invoked to explain the surprising variety of configurations of extrasolar systems, such as the high obliquities in respect to the orbital planes of some exoplanets and the eccentricity distribution of the observed ensemble. It seems that the interaction between the planets and their natal protoplanetary disc, at the early stage of formation, plays an important role for the sculpture of these systems. Resonant eccentricity and inclination excitation during the gas phase ([4], [8], [6]) and planet-planet scattering of unstable, initially coplanar, systems after the dispersal of the disc ([5], [7]) are some of the processes showing that planet-disc interactions play an important role in the diversity of planetary systems. The study of the impact of a well modelled eccentricity and inclination damping on the final configurations of the giant planet systems is the goal of the present work.

2. Methods

We consider initially $\sim$10000 three-planet system embedded in a protoplanetary disc and evolving around a Solar-mass star. We study only systems with gas giant planets that have already formed their massive gaseous envelopes, and so they do not accrete any more material from the disc as they migrate inwards, towards the star. We use the symplectic integrator SyMBA ([3]), which allows us to handle close encounters between the bodies by employing a multiple time step technique. In order to mimic the interaction with the disc and to have a qualitative approach for the timescales of eccentricity and inclination damping, we use the formula provided by the hydrodynamical simulations of [1]. We use two different modelizations of the gas in the disc. In our first method, we introduce a constant-mass approximation for the circumstellar disc. We aim to study the potential establishment of different mean motion resonances and interpret, through statistical analysis, whether the inclination damping has a strong effect on the formation of these resonant configurations. For the second ensemble of simulations, we use a more "realistic" model for the evolution of the protoplanetary disc, decreasing its mass exponentially and setting the dispersal time at $\sim 1Myr$. We stop the interaction with the disc when $\dot{M}_{vis} < 10^{-9} M_{star}/yr$. For both models, our parameter space contains different planetary mass ratios and disc masses. The initial surface density profile of the disc is $\Sigma \propto r^{-0.5}$.

3. Results

We observe a very good agreement between the population of systems obtained by our simulations and the detected one, especially for the eccentricities. In Figure 1, we show the cumulative distribution functions

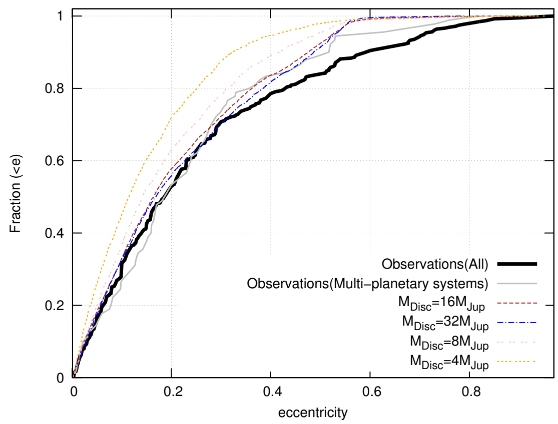

Figure 1: The cumulative distribution functions (CDF) of eccentricity for the observed population of planets with mass $M_p \in [0.65, 10]M_{Jup}$ (black solid line), the detected planets in multi-planetary systems (grey solid line), and our simulated population considering different masses of the disc.

of the eccentricities for the confirmed giant planets with $0.65 < M_p < 10M_{Jup}$ (black solid line – the grey solid line refers to the subset of planets in multi-planetary systems) and the planets resulting from our simulations (four coloured dashed lines, corresponding to different initial mass of the disk). The curves are very similar, except for very low initial disk mass.

The efficiency of the migration mechanism is connected to the surrounding gas in the vicinity of the planet. Therefore, the final semi-major axis distribution depends on the initial mass of the disk and for the first ensemble of our simulations, in which we use a constant-mass model, we observe an overabundance of planets in small distances from the parent star. Nonetheless, removing the gas exponentially, we observe a good matching of our results with the semi-major axis distribution of the observed giant planet population.

Concerning the inclinations, most of the systems are found with small inclinations ($< 10°$) after the dispersal of the gas disk. Despite the fact that many systems enter an inclination-type resonance during the migration phase, the disc damps the inclination in a relatively short time-scale, leading the planets back to the midplane. Nevertheless, a significant fraction of the systems end-up with high mutual inclinations, even for initially massive disk.

Spin-orbit misalignments of Hot Jupiter planets are also observed in the simulated population. However, most of the planets of the final one-planet systems are located in the midplane of the disc. This observation supports the work of [2], showing a possible disc-induced origin to the large fraction of aligned Hot Jupiters currently observed.

Finally, the different resonant configurations reached during the gas phase are investigated thoroughly, and the impact of the eccentricity and inclination damping on the resonance capture in low- and high- resonances is clearly identified.

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