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Formation mechanisms of highly non-coplanar systems

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Abstract

We examine possible dynamical mechanisms for the formation of planetary systems with high mutual inclinations, starting from a coplanar system that undergoes Type II migration in a gas disc. For a three-planet system, an inclination excitation mechanism exists: the three planets can be trapped in a multiple mean motion resonance – as in the case studied in [7], for the young Solar system. As migration continues and the eccentricities of the planets grow, inclination-type resonances come to play. If the resonance persists as the gas dissipates, a stable resonant 3-D three-planet system can form. Otherwise, the system is dynamically disrupted, typically leading to the ejection of one planet and the formation of a highly non-coplanar two-planet system. We show that trapping to several triple resonances can occur and we study the frequency of resonant inclination excitation.

1. Introduction

Recently, the possibility that extrasolar planetary systems can be '3-D systems', namely they are composed of two or more planets whose orbital planes have substantial values of mutual inclinations, has been considered. Some analytical studies have highlighted that such systems can be long-term stable, either following normal secular dynamics or due to the action of a phase-protection mechanism, such as a mean-motion resonance or a Kozai-type resonance (e.g. [6], [2]). Moreover, a first observational confirmation for the υ Andromedae system [5] estimated the mutual inclination of the orbital planes of planets c and d of this system to $\sim 30°$.

Close planetary encounters are commonly thought to produce the inclination excitation of these systems (e.g. [1]). Indeed, if by the end of planet formation, the system is dynamically 'hot', then a phase of planet-planet scattering can be expected; however, this need not be the case in every system. In this work, we examine an alternative scenario for the formation of systems with high mutual inclinations, starting from a coplanar system of three giant planets that undergoes Type II migration in a gas disc.

2. Our model

As recently shown for the case of the Solar system, planetary migration in the gas disc can force the planets to become trapped in a multiply resonant state, an analogue of the Laplace resonance in the Galilean satellites [7]. As the eccentricities of their orbits increase while in resonance, the configuration can become unstable. This can lead to planet-planet scattering and the formation of a highly non-coplanar system.

In [4], we simulated this process, assuming different values for the planetary masses and mass ratios. We showed that this mechanism, combining the action of disc torques and planet-planet scattering, typically results in the ejection of one of the three planets, leaving behind a two-planet system in a nearly hierarchical configuration and with median mutual inclination of $\sim 30°$, this value being close to the one recently obtained for the υ Andromedae system. A small fraction of our surviving two-planet systems ends up in the stability zone of the Kozai resonance. Several simulations result in single-planet systems, which are formed when two planets are ejected from the system; the inclination of the surviving planet's orbital plane with respect to the initial invariant plane - presumably the plane perpendicular to the star's spin axis - can be as large as $40°$. In 10% of the simulations presented in that paper, the triple resonance remains stable for sufficiently long times, leading to the formation of a 3-D system, through resonant inclination excitation: for mild eccentricity damping, the resonance pumps the eccentricities of all planets on a relatively short timescale, to the point where they enter an inclination-type resonance, similarly to the two-body inclination-type resonance observed in [8] and [3].

3. Trapping in three-planet resonances

As also noted in [7], a multiple planetary resonance is a delicate dynamical configuration; not all resonant ratios can be reached by all planetary masses (or mass ratios) and not all resonances are long-term stable. In this work, we examine for what masses of the planets and parameters of the disk a triple resonance can be established, and of what type. Also, we study the frequency of inclination excitation in three-planet resonances. We find that, in general, for planetary masses smaller than $1.5M_J$, multiple resonances of the form n_1:n_2:n_3 =1:2:4 and 1:3:6 are established, as the inner planets get trapped in a 1:2 resonance and the third one subsequently is captured in a 1:2 or 1:3 resonance with m_2. On the other hand, we find that trapping of m_2 in a 2:3 resonance with m_1 occurs very rarely, at least for planetary masses larger than $\sim 1M_J$ and mass ratios $m_2/m_1 > 0.5$, so only few cases of subsequent capture in a three-planet resonance were observed. Concerning the inclination excitation, the multiple resonance pumps the eccentricities of all planets on a relatively short time-scale, so that the systems may enter an inclination-type resonance: mutual inclinations can grow to $\sim 35^\circ$ for mild eccentricity damping.

4. Conclusion

We conclude that the mechanism proposed here is quite robust in producing 3-D planetary systems, characterized by large mutual inclinations. Our results suggest that trapping in a three-planet resonance can be common in exoplanetary systems, provided that the planets are not very massive. Inclination pumping could then occur relatively fast, as long as eccentricity damping is not very efficient, thus forming resonant non-coplanar three-planet systems.

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