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Planet-disc interactions of highly inclined and eccentric massive planets

B. Bitsch (1), A. Crida (1), **A.-S. Libert** (2) and E. Lega (1)
(1) University of Nice-Sophia Antipolis / CNRS / Observatoire de la Côte d'Azur, Laboratoire Lagrange UMR 7293, Boulevard de l'Observatoire, BP4229, 06304 NICE cedex 4, France,
(2) NaXys, Department of Mathematics, University of Namur, 8 Rempart de la Vierge, 5000 Namur, Belgium
(anne-sophie.libert@unamur.be)

Abstract

We investigate planet-disc interactions for planets of several Jupiter masses, considering different inclination and eccentricity values. We show that the inclination of low planetary masses (below $5M_{\rm Jup}$) is always damped. For large planetary masses with large inclination, the situation is more complex: the planet can undergo a Kozai-cycle with the disc. These Kozai-cycles are damped through the disc in time. Eccentricity is generally damped, except for very massive planets (above $5M_{\rm Jup}$) where eccentricity can increase for low inclinations. Thus the dynamics tends to a final state: planets end up in midplane and can then increase their eccentricity due to interactions with the disc. However, a planet scattered to high inclination can undergo a Kozai-cycle with the disc that makes it hard to predict the exact movement of the planet, and its orbital parameters at the dispersal of the disc. This work also provides a general expression of the eccentricity and inclination dampings exerted on the planet by the disc, suitable for long-term evolution studies with N-Body codes.

1. Introduction

While all planets of the Solar System have a small inclination with respect to the equatorial plane, highly non-coplanar extrasolar systems (e.g. υ And) and unexpected spin-orbit misalignment of some exoplanets have been discovered. Two mechanisms, namely scattering by multiple planets after the dispersal of the gas disk (e.g. [3]) and resonant planet-planet interactions during migration in the protoplanetary disc (e.g. [10], [6]), have been invoked to explain the inclined orbits of extrasolar systems. However, the effect of the gas disc on inclined giant planets is still unknown. This work aims at studying the planet-disc interactions of highly inclined and eccentric massive planets.

2. Results of the simulations

We perform three-dimensional numerical simulations of protoplanetary discs with embedded high mass planets ($M_p \geq 1M_{\rm Jup}$) on fixed orbits. We use the explicit/implicit hydrodynamical code `NIRVANA` in 3D [1], with an isothermal equation of state.

The simulations were performed for 10 inclination values of the planet, ranging from $i = 1.0°$ to $75°$, and 3 eccentricity values ($e = 0$, 0.2, 0.4). For highly inclined massive planets, the gap opening is reduced, and the damping of i occurs on time-scales of the order of $10^{-4}{\rm deg/year} \cdot M_{\rm disc}/(0.01M_\star)$, with the damping of e being on a smaller time-scale.

It is known that massive planets can change the shape of the whole disc by turning it eccentric (e.g. [7]). Additionally, we show that the inclination of the disc will also change due to the interactions with the inclined planet: the disc inclination is increased mostly around the planet location and can be larger than the inclination of the planet. In turn, the disc acts on the planet modifying its orbital parameters. In the present work we have calculated the forces exerted on a planet on a fixed orbit in order to determine the rate of change of the inclination and eccentricity. We provide damping formulae for the inclination and the eccentricity of the planet as a function of i, e, and M_p that fit the numerical data (see [2]).

The eccentricity of the planet is damped in all the simulations, except for very massive planets on low inclination, whose eccentricity can rise, as already shown by previous studies (e.g. [7]). Also the inclination of the planet is always damped, except for very massive planets on large inclination. Both damping rates significantly increase with increasing planetary eccentricity for all planetary masses. For $1M_{\rm Jup}$ the damping rate of e and i is highest only for very small inclinations ($\sim 3°$), while the maximal damping rate is shifted to larger inclinations for more massive planets.

Simulations of planets evolving freely in the disc have indicated that the evolution of highly inclined massive planets ($i > \sim 40°$) is quite different from what was expected after several orbits: the gravitational force exerted by the disc on the planet produces Kozai cycles where the eccentricity of the planet can be pumped to high values, in antiphase with its inclination. These exchanges of inclination and eccentricity are representative of the Kozai mechanism affecting the orbits of highly inclined planets with respect to a disc (e.g. [8], [9]). Let us note that the Kozai mechanism is visible in the given computation time because of the high mass values considered in our study, comparable to the total mass of the disc ($0.01 M_{\odot}$). Even if eccentricity can be pumped to high values, the Kozai mechanism only postpones the alignment with the disc and the circularization of the orbit induced by damping forces of the disc on the planet. So, our damping formulae are only valid for planet inclination lower than $\sim 40°$, since a Kozai-cycle with the disc makes it hard to predict the exact movement of the planet, and its orbital parameters at the dispersal of the disc.

As a result, planets scattered on highly inclined orbits will follow a certain pattern. As the inclination is damped slowly and still high, the eccentricity is damped to zero. In the end, the inclination will also be damped to zero, and low mass planets ($M_p < 4 - 5 M_{\rm Jup}$) will end up on circular orbits in midplane of the disc, while higher mass planets ($M_p > 5 M_{\rm Jup}$) will pump their eccentricity to larger values, due to interactions with the disc.

3 Conclusion and Perspectives

These results imply that if a planet is scattered to high inclined orbits while the gas disk is still present, it will be brought back to the midplane by the disk. For the inclination to remain observable today, the scattering must have taken place after the gas disk dispersal. But this has been proven unlikely by [4].

More promising is the excitation of inclination by resonant interactions between two migrating giant planets (see [10], [5]). The study of this mechanism, taking into account the inclination damping by the proto-planetary disk found here, will be the topic of our future work.

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