Interaction between inclined massive planets and circumstellar discs

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Abstract

We use SPH simulations to study the orbital evolution of a massive planet as well as the dynamical response of the disc for planet masses between 1 and $6\ \mathrm{M_J}$ and the full range of initial relative orbital inclinations. At high relative inclinations, the inclination decay rate increases for increasing planet mass and decreasing initial relative inclination. For an initial semi-major axis of 5 AU and relative inclination of $i_0 = 80^\circ$, the times required for the inclination to decay by 10° is $\sim 10^6$ yr and $\sim 10^5$ yr for $1\ \mathrm{M_J}$ and $6\ \mathrm{M_J}$. This indicates that planets with mass $1\ \mathrm{M_J}$ initiated in circular orbits with semi-major axis ~ 5 AU and $i_0 \sim 90^\circ$ might only just become coplanar, as a result of frictional effects, within the disc lifetime. In other cases highly inclined orbits will survive only if they are formed after the disc has mostly dispersed. Planets on inclined orbits can warp the disc quite significantly. In that case of $M_p = 6\ \mathrm{M_J}$, the disc can gain a total inclination of up to 15° together with a warped inner structure with an inclination of up to $\sim 20^\circ$ relative to the outer part. We also find a solid body precession of both the total disc angular momentum vector and the planet orbital momentum vector about the total angular momentum vector. Our results illustrate that the influence of an inclined massive planet on a protoplanetary disc can lead to significant changes of the disc structure and orientation which can in turn affect the orbital evolution of the planet significantly. A three-dimensional treatment of the disc is then essential in order to capture all relevant dynamical processes in the composite system.

1 Introduction

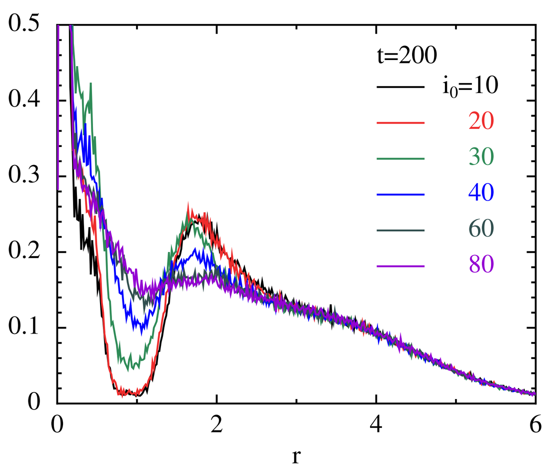
We extend current studies of disc planet interactions involving planets with orbital planes misaligned with that of the disc to consider larger planet masses of up to several Jupiter masses and the full range of inclinations. In such cases the interaction with the disc is more likely to be described by dynamical friction than being the result of the application of resonant torques that is applicable in the coplanar case. SPH simulations can be readily used to simulate a gas disc with a free boundary in three dimensions with the disc having the freedom to change its shape at will. For this reason, we take the N-Body/SPH code GADGET-2 (Springel 2005). We study the response of the disc and estimate the timescales for orbital evolution and attainment of coplanarity. We also make a preliminary study of the potential exchange of inclination and eccentricity that might be expected for high inclination orbits through the operation of an adaption of the Lidov-Kozai mechanism.

2 Simulation details

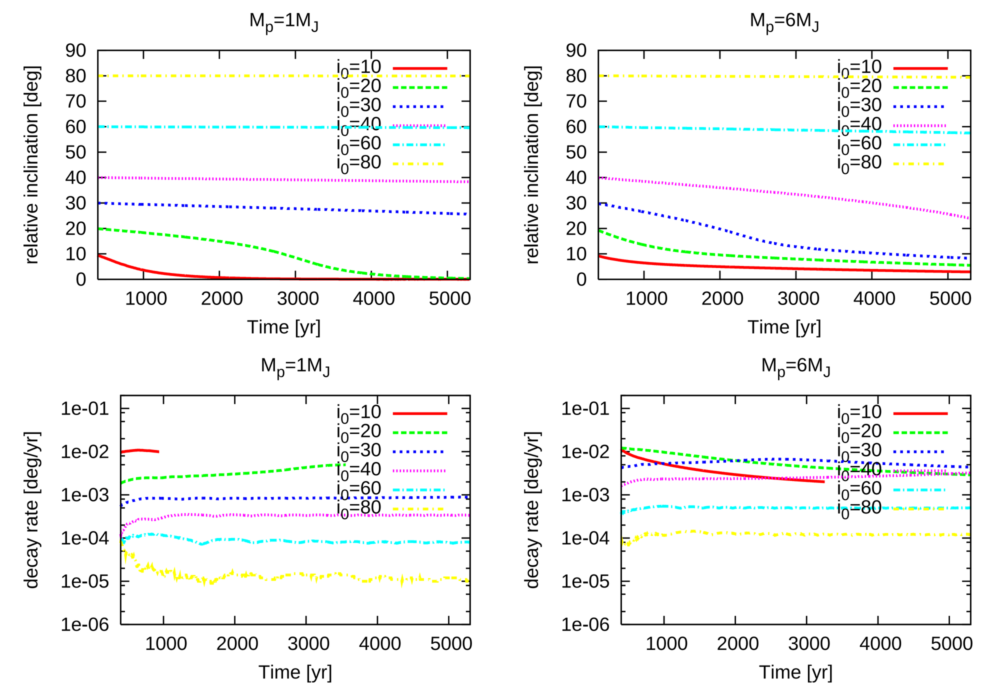
We study a system composed of a central star of one solar mass $\mathrm{M_\odot}$, a gaseous disc and a massive planet. Planet masses in the range 1 - $6\ \mathrm{M_J}$ were initiated in circular orbits with inclinations in the range $i_0 = [0;80]^\circ$ with respect to the initial disc mid plane. The semi-major axis of the planet was set to $a = 5$ AU. The disc has an aspect ratio $H/r = 0.05$. We applied a locally isothermal equation of state with the modification described by Peplinski (2008). The artificial viscosity parameter α of GADGET-2 was taken to be $\alpha = 0.5$. The total disc mass is 0.01 $\mathrm{M_\odot}$ and extends from 0 to 25 AU. The surface density profile is $\Sigma = \Sigma_0 R^{-1/2}$. The star and the planet are treated as sink particles that can accrete gas particles.

At the start of a simulation, the disc is allowed to evolve for 30 orbits before the planet is introduced. The number of SPH particles was then chosen to be 2 $\times 10^5$ for most of our simulations . For more details see Xiang-Gruess & Papaloizou (2013).

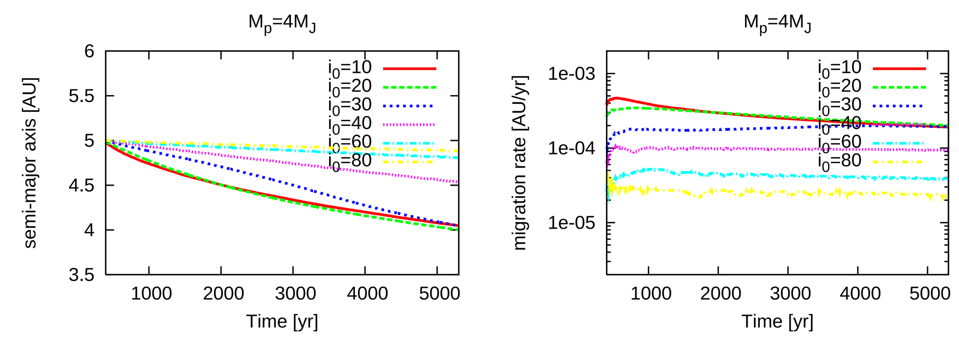
3 Results



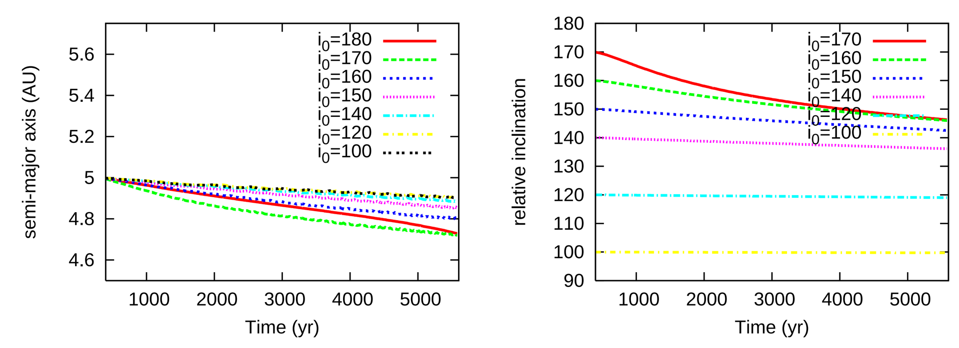
Gap formation is dependent on planet mass and relative inclination. For very high $i_{rel,0}$, Σ is marginally perturbed for $M_p = 6\ \mathrm{M_J}$. With decreasing $i_{rel,0}$, the interaction between the planet and the disc becomes stronger until eventually the threshold below which a noticeable gap starts to form is passed. For $M_p = 1\ \mathrm{M_J}$, only the $i_0 = 10^\circ$ curve is able to open a noticeable partial gap. For $2\ \mathrm{M_J} \leq M_p \leq 6\ \mathrm{M_J}$, the threshold initial inclinations are $i_0 = 20^\circ, 30^\circ$ and 40°, respectively.



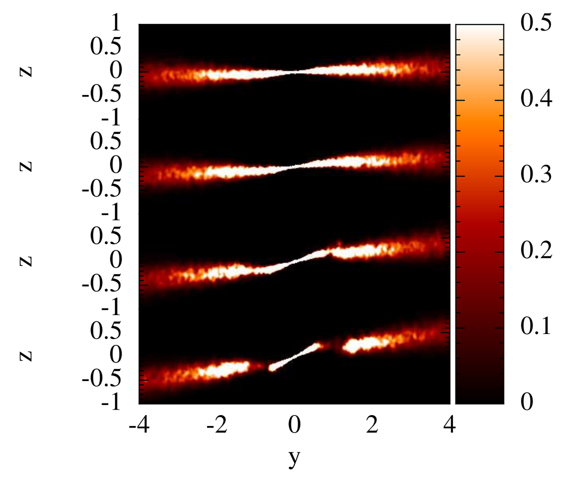
Estimate of decay time scales:
$i_0 = 10^\circ$, $1\ \mathrm{M_J}$: $T_D \sim 10^3$ yr.
$i_0 = 80^\circ$, $1\ \mathrm{M_J}$: $T_D \sim 10^7$ yr.
Small to intermediate i and larger planet masses, the i-decay is strongly dependent on gap formation, i decreases at an accelerating rate towards smaller values as long as no gap is formed. As soon as i is sufficiently small to open a gap in the disc, the rate of inclination decrease slows down. At large i_{rel}, the inclination decay rate increases with planet mass so that for $i_0 = 80^\circ$, the decay rate is an order of magnitude faster for $6\ \mathrm{M_J}$ as compared to $1\ \mathrm{M_J}$.



For planets starting on inclined orbits, the migration rate is slower than for the coplanar case due to the reduced interaction of the planet with the disc.

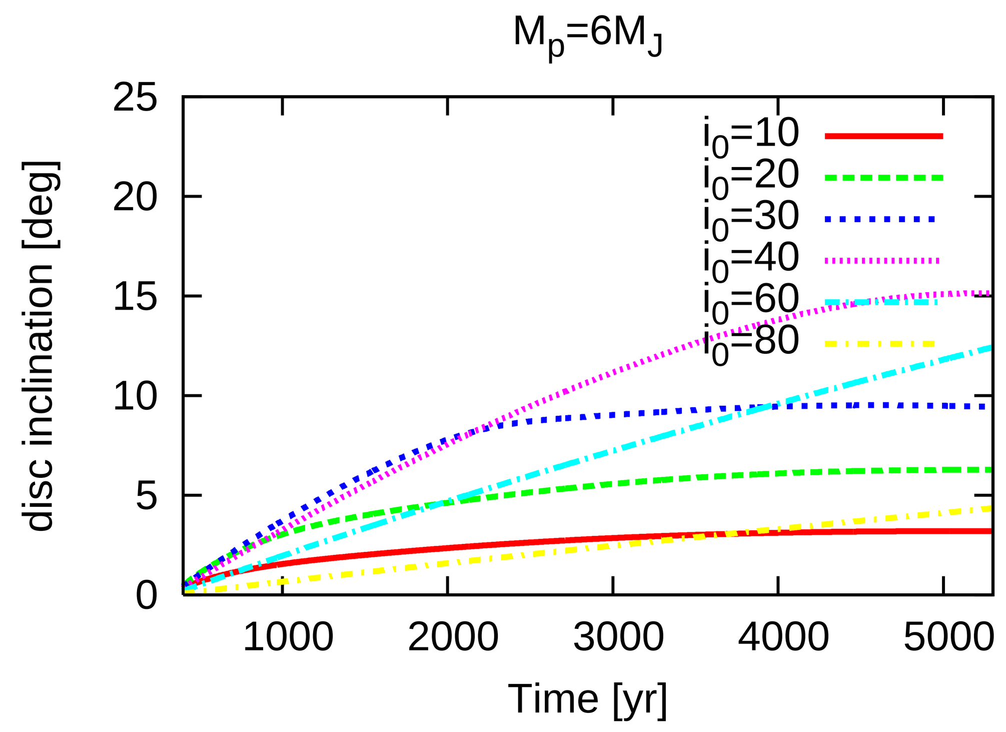


The direction of evolution of the inclination is always towards coplanarity ($i_{rel} = 0^\circ$). This is to be expected from a frictional interaction between the planet and the disc which tends to communicate angular momentum in the direction of the disc's angular momentum vector to the orbit of the planet. Most rapid evolution for the largest inclinations for which the planet tends to become embedded in the disc and thus undergo a more sustained frictional interaction.

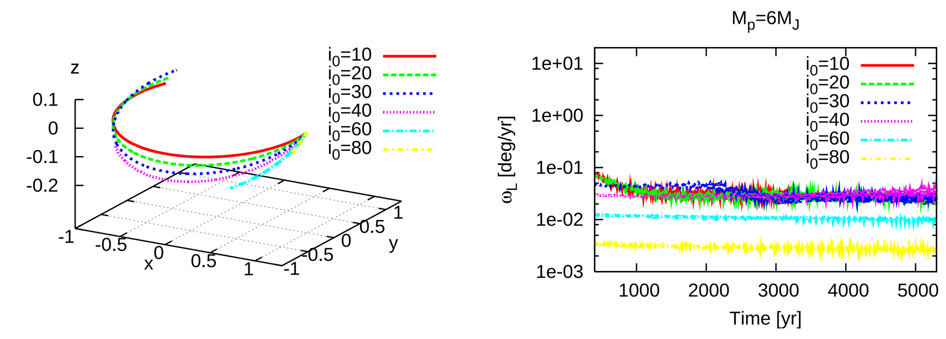


Cross section (density distribution) at $x = 0$, $i_0 = 30^\circ$ and after 200 orbits. Visible warped inner section of the disc produced by the more massive planets while planets with $M_p = 1$ and $2\ \mathrm{M_J}$ do not succeed in creating a visibly warped disc.

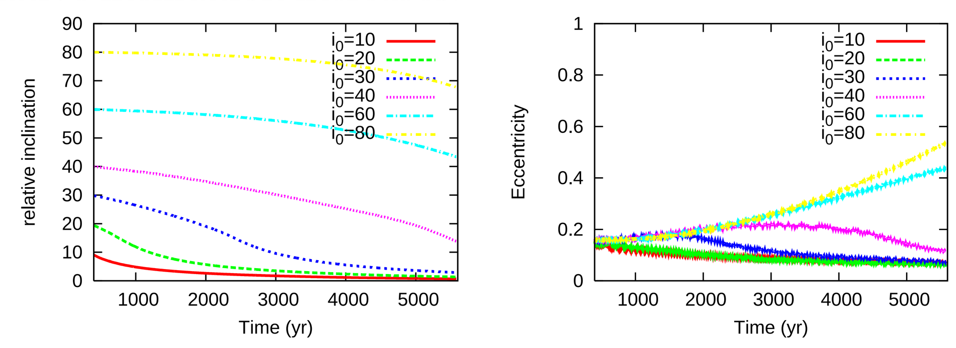
M_p [$\mathrm{M_J}$]	i_0 [deg]	i_{rel} [deg]	α_{warp} [deg]
4	30	17.0	10.4
6	30	14.6	19.1
6	40	34.8	10.7



Effect of the planet is strongest for $i_0 = 45^\circ$. For $6\ \mathrm{M_J}$, the total disc inclination only attains values up to 15°.



F_g of a disc with a planet in an inclined orbit $\Rightarrow$ precession of the orbit about the total angular momentum vector of the system. Precession velocity almost constant when $i_{rel} \cong$ const, it decreases as the relative inclination increases which is expected as a reflection of the decrease in magnitude of the precessional torque acting between the planet and the disc as the relative inclination increases.



Initial orbital eccentricity of 0.15: e decay for $i_0 \leq 40^\circ$. For $i_0 = 60^\circ$ and $i_0 = 80^\circ$: significant $e > 0.4$ developed and were increasing at the end of the simulations + decrease of i_{rel}. Possible Lidov-Kozai cycle.

4 Conclusions

We have performed SPH-simulations in order to undertake a systematic study of the interaction of planets with masses in the range $1-6\ \mathrm{M_J}$ with initial inclinations in the range $[0;80]^\circ$ with a circumstellar disc. For a disc mass of $0.01 M_\odot$, $i_0 = 80^\circ$ and $6\ \mathrm{M_J}$, the time to decay through 10° was found to be $\sim 10^5$ yr while for $1\ \mathrm{M_J}$, it is $\sim 10^6$ yr. For small to intermediate i_0, gap formation plays a crucial role in the determination of the inclination decay rates. Planets with larger masses are able to form gaps at higher relative inclinations. The reduced amount of material near the planet then causes the frictional interaction to be reduced with a corresponding reduction in the inclination decay rate. After 200 orbits, we find the threshold initial relative inclination below which gap formation starts to occur to be $i_0 = 10^\circ$ for $M_p = 1\ \mathrm{M_J}$, $i_0 = 20^\circ$ for $M_p = 2\ \mathrm{M_J}$, $i_0 = 30^\circ$ for $M_p = 4\ \mathrm{M_J}$ and $i_0 = 40^\circ$ for $M_p = 6\ \mathrm{M_J}$, For the case of a $4\ \mathrm{M_J}$ planet initiated on a retrograde circular orbit and different initial inclinations, we found that the direction of evolution tends towards coplanarity ($i = 0^\circ$). Visible warping occured in the inner parts. The difference between the inclinations of the inner and outer part of the disc was found to attain up to $10-20^\circ$. The total disc orientation can change by up to $\sim 15^\circ$ with respect to its original mid plane. retrograde precession of both the the total disc angular momentum vector and the planet's angular momentum vector about the conserved angular momentum vector of the system has also been found.

Our results are reasonably consistent with theoretical estimates of evolution time scales from dynamical friction, although the simulated behaviour of the disc turns out to be complex in some cases and was not taken into account. In contrast to the situation with low-mass planets, the results suggest that the interaction of a massive planet with a disc can lead to a strong distortion. Furthermore the stronger frictional interaction is likely to lead to coplanarity within disc lifetimes in most cases. Thus highly inclined orbits are only likely to survive if they are formed after the disc has mostly dispersed.

Acknowledgements

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References

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