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MIGRATION OF PAIRS OF GIANT PLANETS IN LOW VISCOSITY DISCS.

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Abstract. In classical viscous discs Jupiter and Saturn are most often locked in the 3:2 mean motion resonance and may migrate outwards. Instead in low viscosity disks we find, using 2D hydrodynamical simulations, that the pair of planets gets locked in either the 5:2 or the 2:1 resonance and has a slow inward migration. We confirmed this result for a range of disc masses and thicknesses as well as different starting positions of Saturn. This result is also independent of the mass of the outer planet. The only case in which outward migration is observed (and therefore is compatible with the Grand Tack model) is a scenario where Saturn would form inner to the 2:1 resonance and get locked in the 3:2.

Keywords: **Planets: formation, proto-planetary disks,** planetary migration

1 Introduction

Planets form in protoplanetary discs and their interactions with the gas give rise to migration. For a long time, discs were believed to have a non-negligible viscosity to justify the high accretion rates of gas onto the central star. However, it has recently been shown observationally and theoretically that protoplanetary discs are probably much less viscous than previously thought. In our study, we use a new paradigm for the theoretical modelling of discs where the accretion onto the central star is done through the superficial layers while the mid-plane has a close to zero viscosity (Lega et al. 2022). In such discs, the migration of a single giant planet differs from the classical Type-II migration regime and depends on the thickness of the accretion layer. It is therefore interesting to consider the migration of a pair of giant planets in this new model. We have started this project, in the simplified framework of 2D hydrodynamical simulations studying a pair of Jupiter and Saturn mass planet.

2 Method

In this work, we consider a protoplanetary non-self gravitating disc made of gas only. We adopt a flared aspect ratio given by Chiang & Goldreich (1997) such that $h = h_0(r/r_0)^{2/7}$ with $h_0 = 0.05$, in the nominal case. The disc density is given by $\Sigma = \Sigma_0(r/r_0)^{-1/2}$ where r_0 is the distance unit and $\Sigma_0 = 6.76 \cdot 10^{-4}$ in code units (i.e. $M_* {r_0}^{-2}$) for the nominal case. We use the α-prescription (Shakura & Sunyaev 1973) for the kinematic viscosity, such that $\nu = \alpha h^2 \Omega$, with Ω the angular velocity and$\alpha = 10^{-4}$, instead of the standard 10^{-3}. This value is observationally and theoretically motivated. Moreover from a numerical point of view it has been shown that numerical convergence cannot be obtained for values of α lower than $5 \cdot 10^{-5}$ (McNally et al. 2019). We run 2D simulations with the code FARGOCA (Lega et al. 2014). The resolution used in all simulations is of about 7 grid cells per scale height for our nominal simulation.

Our simulations proceed as follows. First, we let Jupiter grow on a fixed orbit, then let it migrate alone in the disc for a few thousand years. In our nominal simulation, Saturn forms at the edge of Jupiter's gap near a pressure maximum. This location is motivated by studies showing that dust traps could be the birthplace of planetary formation (Eriksson et al. 2021, and references therein). The planet mass is then increases smoothly up to Saturn's mass in 800 local initial orbits and the planet is allowed to migrate during its growth. We see in Fig. 1 the density distribution of the disc at different stages of the simulation. Panel a shows the moment of introduction of Saturn in the disc. Panel b shows Saturn, at 45% of its final mass, transitioning from a wake driven migration to carving its own gap. The gap is fully opened in panel c, once the planet is close to its final mass. At last, panel d of Fig. 1 shows the disc surface density after 118 000 years, when Jupiter and Saturn are migrating together in a common gap.

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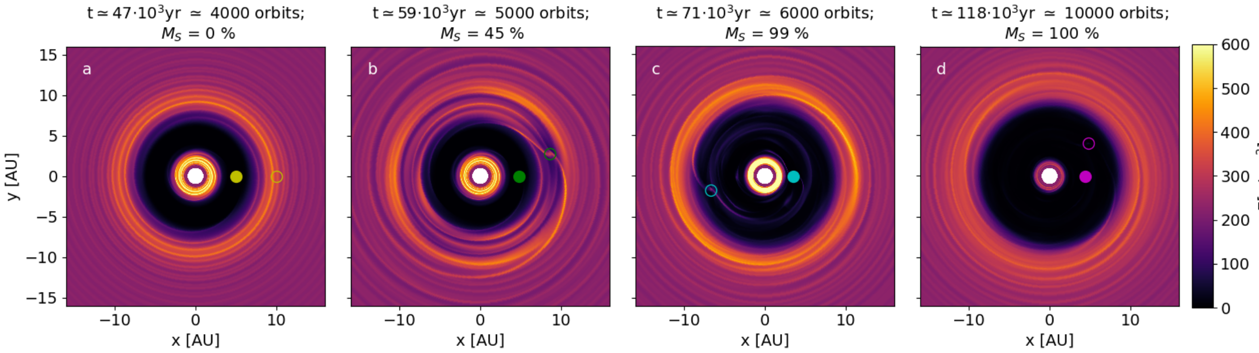

Fig. 1. Surface density of the disc at different time of the nominal simulation. The filled and empty circles mark the positions of Jupiter and Saturn respectively. The colors given to the planets corresponds to the markers in Fig. 2

3 Results

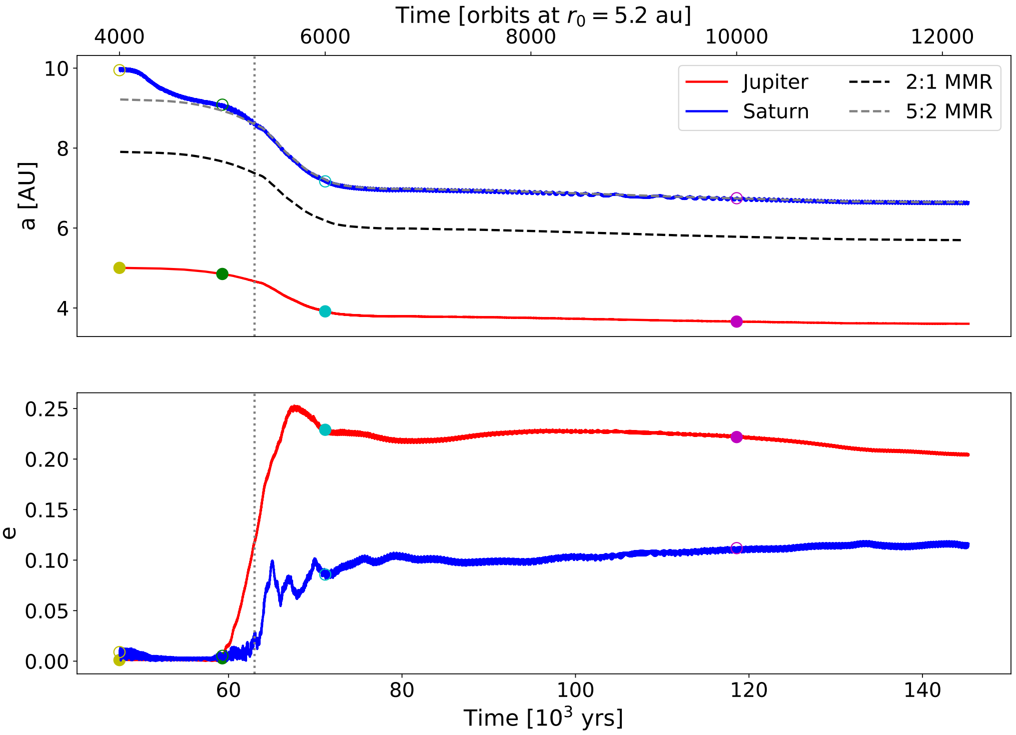

Fig. 2. Orbital parameters evolution of Jupiter and Saturn in the nominal simulation. The top panel shows the semi-major axes of Jupiter in red and Saturn in blue. The grey and black dashed lines mark the positions of the 5:2 and 2:1 resonances with Jupiter respectively. The dotted vertical line marks the moment at which all four resonant angles corresponding to the 5:2 MMR start librating. The bottom panel shows the eccentricities of the planets. At the start of these curves Jupiter is fully grown, while Saturn reaches its final mass around 72 700 years. The colored markers indicate the times at which the surface density is represented in the four panels of Fig. 1

In our nominal simulation, we find that Saturn while migrating towards Jupiter, gets trapped at the density bump located at the edge of Jupiter's gap. At a low viscosity, the gap formed by Jupiter is deeper and most importantly wider than in higher viscous discs. In the case of $\alpha = 10^{-4}$ and for an aspect ratio of $h_0 = 0.05$ (corresponding to our nominal simulation), the density maximum which serves as a planet trap, is located beyond the 5:2 MMR with Jupiter. As a result of this location Saturn becomes captured in the 5:2 MMR with

Jupiter. Once in resonance, both planets migrate slowly inwards together, as shown in Fig. 2.

We further explore this scenario with a parameter study varying the aspect ratio and the mass of the disc as well as the initial distance between the planets. We found that the pair of planets ends locked in either the 5:2 or the 2:1 MMR. This outcome depends on where the planet trap is located with respect to the resonances and/or if Saturn destroys this planet trap by opening its own gap. Generally, we find that in all our simulations Saturn never crosses the 2:1 MMR with Jupiter. This result is in contrast with those in classical viscous discs (corresponding to an $\alpha \geq 10^{-3}$). Indeed, Jupiter and Saturn systems are most often locked in the 3:2 mean motion resonance and may migrate outwards, in viscous discs (Masset & Snellgrove 2001; Pierens & Nelson 2008; Morbidelli & Crida 2007).

Therefore, we assess the relevant question: why is the 2:1 resonance never crossed at low viscosity ? Fig. 3 shows that at low viscosity, the migration of a planet departs from the type I regime at a lower planetary mass than in the high viscosity case. Therefore the maximal migration speed reached by the planet in a low viscous disc is much smaller than in a disc with viscosity $\alpha = 10^{-3}$. In Griveaud et al. (2022, in prep.), we show using an analytical criterion for resonance crossing based on Batygin (2015), that a planet growing and migrating in a low viscosity disc never reaches the migration speed required to cross the 2:1 MMR.

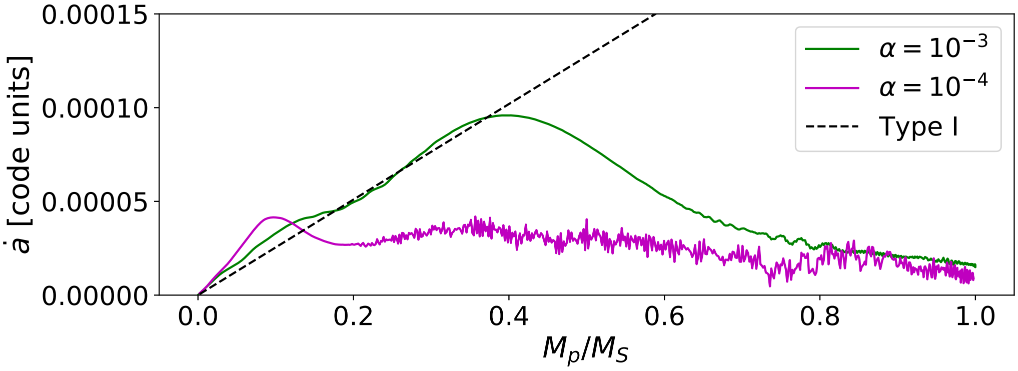

Fig. 3. Migration speed of a planet growing and migrating in an unperturbed disc, as a function of its mass (given in Saturn mass M_S), for the two different viscosity parameters $\alpha = 10^{-3}$ and $\alpha = 10^{-4}$. The dashed black line shows the analytical type I migration speed from Tanaka et al. (2002) (with $r = 1$ constant), which we recall is independents of viscosity.

Lastly, the only case in which outward migration is observed, is the "ad-hoc" scenario where Saturn would form inside the 2:1 resonance and get locked in the 3:2. However, owing to the large width of Jupiter's gap, this scenario seems unlikely.

4 Conclusions

We find that in low viscosity discs, the migration of a Jupiter and Saturn pair of planets always result in the planets locking in either the 5:2 or the 2:1 mean motion resonance and migrate slowly inwards. We confirm this for a wide range of parameters. These results bring new possibilities in the evolution models of planetary systems. Indeed, if the Solar System formed from such a low-viscosity disc, this result has strong implications for the Grand Tack and Nice models, which both assume Jupiter and Saturn to be inside **of** the 2:1 resonance. The slow migration could, however, explain the so called warm-Jupiters population among the detected exoplanets, providing that these are in multi-planet systems. Additionally, we remark that the only system with two giant planets observed in a disc of gas, namely PDS70, occurs to be close to the 2:1 resonance.

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