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Migration of giant planets in low viscosity discs and consequences on the Nice model

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Abstract. Using 2D hydrodynamical simulations, we show that in a low viscosity protoplanetary disc, Jupiter and Saturn get locked in the 2:1 mean motion resonance and migrate slowly inwards, unlike cases at higher viscosities. We conclude that in such discs the scenario of the Grand-Tack is not possible. Additionally, we investigate how the migration of the four (potentially five) giant planets in low viscous discs may affect the initial conditions of another important model for the formation history of our Solar System: the Nice Model. Adding ice giants in our hydrodynamical simulations, we find different possible resonant chains induced by migration. We then let the disc evolve until the gas phase dissipates and study the dynamical stability of the system. We find it possible to recreate the Solar System from such resonant chains, however the likelihood of this outcome remains low.

Keywords. Planets-disc interactions, protoplanetary discs, planetary systems

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1. Introduction

Planets form in protoplanetary discs and their interactions with the gas give rise to migration. In most cases, if multiple planets form in a disc, they undergo convergent migration and get locked in resonance with one another. In the case of our Solar System, several works have studied the migration of Jupiter and Saturn (e.g. Masset & Snellgrove 2001; Morbidelli & Crida 2007). The resonance chains planets form strongly depends on how the planets migrate and therefore on the disc's parameters.

At the time of these cited studies, discs were believed to evolve under the effect of a significant viscosity (attributed to turbulence), characterised by a dimensionless α parameter (Shakura & Sunyaev 1973) in the interval $[10^{-3}, 10^{-2}]$. However, recent observations of dust settling have allowed Pinte et al. (2016) and Villenave et al. (2022) to derive values of α of the order of 10^{-4} and 10^{-5} respectively. Such low turbulence and viscosity levels are also supported by recent theoretical developments (e.g. Turner et al. 2014, for a review). In our study, we therefore revisit the migration of multiple giant planets in low viscosity discs.

2. Protoplanetary disc phase: hydrodynamical study

We run 2D global hydrodynamical simulations with the grid-based code FARGOCA†. We set the Shakura & Sunyaev (1973) viscosity parameter to $\alpha = 10^{-4}$.

† A recently re-factorised version of the code that can be found at: https://gitlab.oca.eu/DISC/fargOCA

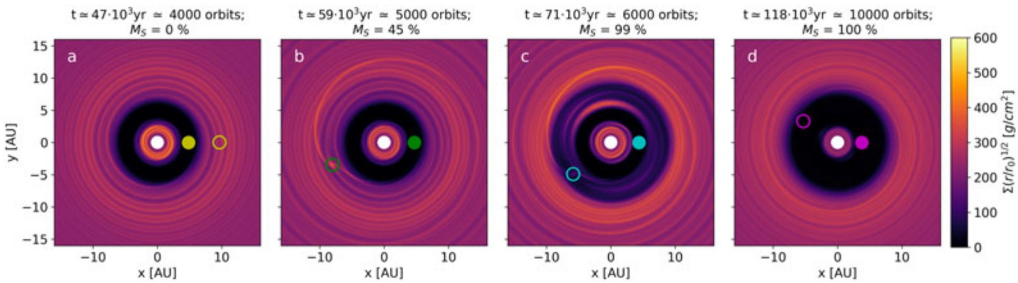

Figure 1. Surface density of the disc at different times of a simulation (as seen in Griveaud et al. 2023). The filled and empty circles mark the positions of Jupiter and Saturn, respectively. Panel a shows the disc at the moment of introduction of Saturn, while the outer planet still has zero mass. In panels b and c, the planet is at 45% and 99% of its total mass, respectively. Panel d shows the disc and the planets closer to the end of the simulation, when both planets are in a large common gap and locked in the 2:1 MMR.

2.1. *Migration of Jupiter and Saturn*

The simulation starts with a planet on a fixed circular orbit whose mass is increased analytically from zero up to Jupiter's mass in 800 local orbits. We wait an additional 400 orbits to let the disc stabilise before allowing Jupiter to migrate. This process avoids triggering instabilities that could arise from introducing a Jupiter mass planet in the disc directly (Hammer et al. 2017; Hallam & Paardekooper 2020). Once Jupiter is migrating smoothly, we add Saturn into the system. The second planet's mass grows similarly to the first one, but it is allowed to migrate as it grows. Figure 1 shows the different stages of a simulation. Panel b shows that Saturn's migration is dominated by its gravitational wake, so the planet is in type I regime at this stage. Panel c on the other hand shows that Saturn starts opening its gap, therefore transitioning from type I to type II migration.

While migrating, Saturn gets locked into the 2:1 mean motion resonance (MMR) with Jupiter. This increases Jupiter's eccentricity to ~ 0.1. Figure 2 shows up to $150 \cdot 10^3$ years the evolution of the semi-major axis of both planets, where the shaded areas represent the radial extent between peri- and apo-center. Both planets continue to migrate slowly inwards (see section 2.3). This result is in contrast with the one of classically viscous discs ($\alpha \geq 10^{-3}$), in which the planets are found most often in the 3:2 MMR.

We extended our study to a wide range of disc parameters to assess the robustness of our result and consistently found capture in the 2:1 MMR. In the case where the aspect ratio is smaller than in the nominal simulation, we find that the planets get locked in the 5:2 MMR. This is explained by the presence of an over density of gas at the edge of Jupiter's gap acting as a planet trap for the growing Saturn. This over density coincides with the location of the 5:2 MMR with Jupiter, allowing Saturn to enter very slowly into this resonance. Nevertheless, we find that in all our parameter exploration, Saturn never crosses the 2:1 MMR with Jupiter, unlike in the classically viscous case.

We explain those results by comparing the migration speed in a simulation of a planet growing and migrating in a low-viscosity disc, with an analytical critical migration rate for resonance crossing (adapted from Batygin 2015). The maximum migration rate reached by the planet is way below that of the critical rate to cross the 2:1 MMR. Therefore we conclude that it is not possible for any outer planet to cross the 2:1 MMR with a Jupiter mass planet in a low viscosity disc. The reader is referred to Griveaud et al. (2023) for more details.

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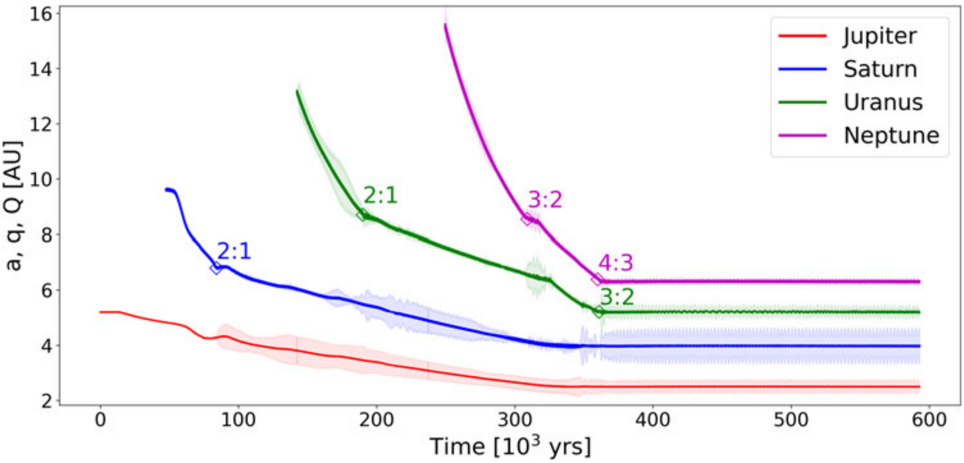

Figure 2. Orbital parameters' evolution of Jupiter, Saturn, Uranus and Neptune in the nominal simulation. The shaded areas mark the positions of the peri- and apo-centre, $q = a(1-e)$ and $Q = a(1+e)$, of the planets, respectively. The beginning of the plot shows Jupiter growing on a fixed orbit, then migrating alone in the disc. Saturn is introduced in the system at about 48 000 years, and gets caught in the 2:1 MMR with Jupiter at about 83 000 years. This phase corresponds to section 2.1. Uranus and Neptune are added consecutively in the simulation and the final resonance chain is (2:1, 3:2, 4:3). Here Neptune's introduction time was $T_{N,0} = 250\,000$ years (see Fig. 3)

2.2. *Building resonance chains*

As a follow-up to Griveaud et al. (2023), aiming at reproducing the Solar System, we now add a third planet with a Uranus mass, in the nominal simulation shown above. In Fig. 2, we show the evolution of the planetary system. Uranus gets initially locked the 2:1 MMR with Saturn. Once the system with three planets is stabilised, we add a fourth planet with the mass of Neptune. When Neptune approaches the 3:2 MMR with Uranus it excites its eccentricity which eventually leads to Uranus being ejected out of both resonances. The two ice giants continue to migrate inwards until Uranus gets locked in the 3:2 MMR with Saturn. At the same time, Neptune locks itself in the 4:3 MMR with Uranus, coincidentally also the 2:1 MMR with Saturn. The system remains stable in a compact chain.

Exploring the stability of such systems, we tried introducing Neptune at a different time. This is shown in Fig. 3. Like previously, Neptune kicks Uranus out of the 2:1 MMR with Saturn however, now Uranus is ejected out of the system after a succession of close encounters with the gas giants (see Fig. 3 at $355 \cdot 10^3$ years). Despite this short instability moment, Neptune is captured in the 2:1 MMR with Saturn and the system of now three planets remains stable. We then add another Uranus mass planet in the disc. This new ice giant migrates inwards, gets locked in the 4:3 MMR with the previous one, and the system remains stable.

These simulations show the sensitivity of the system to the time of introduction of the outer planets. Indeed, in low viscosity discs, gaps carved by giant planets are much deeper and wider than in classically viscous discs. Consequently there is less dissipation around the planets and therefore the resonance chains are weaker. We explored which other resonant chains the planets form by modifying further the time of introduction of the outer planets as well as by considering a colder disc (i.e. smaller aspect ratio). We also added a fifth planet in some systems, motivated by previous studies of the Nice Model. Table 1 summarises the stable systems obtained from our simulations. We note

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Table 1. Summary of the resonance chains obtained from hydrodynamical simulations, based on the disc property, the number and order of planets. The last three columns show results of N-body simulations presented in section 3 for the cold disc cases and for planetesimal disc mass M_D. See text for the criteria. The nominal disc's N-body simulations are a work in progress.

Disc	Planet order	Resonant chain	M_D	Crit. A	Crit. B
Nominal	J-S-N-U	(2:1, 2:1, 4:3)			
Nominal	J-S-U-N	(2:1, 3:2, 4:3)			
Nominal	J-S-N-U-U	(2:1, 2:1, 4:3, 5:4)			
Cold	J-S-U-N-P9	(2:1, 3:2, 5:4, 4:3)	$30M_\oplus$	5.6 %	4 %
Cold	J-S-U-N	(2:1, 3:2, 5:4)	$30M_\oplus$	8 %	4 %
			$50M_\oplus$	9.5 %	5.5 %

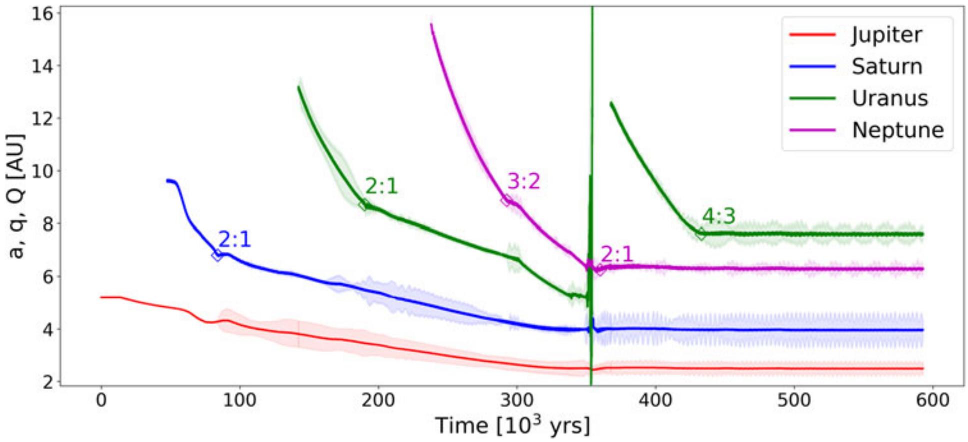

Figure 3. Same as Fig. 2 but with Neptune's introduction time $T_{N,0} = 238\,000$ years. The final resonance chain is (2:1, 2:1, 4:3).

that in the cold disc case, when adding a fifth ice giant, the system is unstable. Instead we were able to add a planet of mass $M_p = 6M_\oplus$, corresponding to the estimated mass of Planet Nine (Brown & Batygin 2021).

2.3. *Migration rate of giant planets in resonance*

In viscous discs, where Jupiter and Saturn are most often in 3:2 MMR, they can reverse their migration and move outwards in the disc (Masset & Snellgrove 2001). This permits the Grand-Tack scenario (Walsh et al. 2011) in which Jupiter first migrates in, then outwards when it reaches 1.5au once Saturn catches up with it. In contrast, here we find that Jupiter and Saturn, in the 2:1 (or 5:2) MMR keep migrating inwards, although more slowly than a single planet. Thus, in Griveaud et al. (2023), we concluded that the Grand Tack scenario is not possible in low viscosity discs.

Interestingly however, we notice that in both cases shown in the previous sub-section, adding two ice giants in the system halts remarkably the inward migration of Jupiter and Saturn. This may help keeping the Solar System giant planets far from the Sun. Their subsequent evolution to their present orbit, after the gas is gone, is the topic of next section.

3. Giant planets instability: N-body study

Once we have obtained some stable resonant chains between 4 or 5 planets, we are interested in studying whether these resonant configurations can recreate the Solar System

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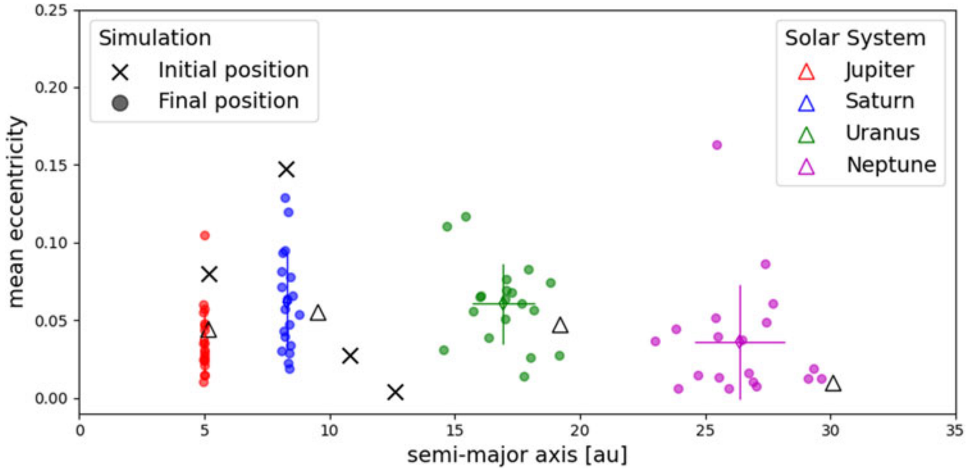

Figure 4. Final orbits of the four giant planets after their interaction with an outer disc of planetesimals (Nice model). The initial positions of the planets are given by the black crosses, corresponding to the (2:1, 3:2, 5:4) resonant chain. Only the cases with four planets at the end of the simulation are shown here (~ 10% cases). The bars show the mean and standard deviation of the distribution of orbital parameters for each planet. For reference, the currents position of the Solar System planets are given by the triangles.

after some interactions with a planetesimal disc : the Nice model (Tsiganis et al. 2005). We gradually remove the gas from our hydrodynamical simulations. Using the orbital parameters of the planets outputted by the code FARGOCA, we initialise the same system in the N-body library `rebound` (Rein & Liu 2012). Using the hybrid integrator `Mercurius` (Rein et al. 2019) we integrate the system for a few hundreds of millions of years. In Fig. 4, we show the results of such simulations in the case where we add a planetesimal disc of mass $50M_\oplus$ positioned from 0.5au away from the outer most planet and up to 30au. Starting from the (2:1, 3:2, 5:4) resonant chain, about 10% of the simulations maintain four planets in an order comparable to the current Solar System† (criterion A of Nesvorný & Morbidelli 2012). In about half of them, the semi-major axes of the planets are within 20% of the solar system values and their eccentricities less than 0.11 (criterion B of Nesvorný & Morbidelli 2012, without inclinations).

The analysis of the other resonance chains is in progress, but our preliminary results shown in Table 1 are less favourable. An exploration of the parameters of the disc of planetesimals may be necessary and is the subject of on-going work (Griveaud et al. *in prep.*).

4. Conclusion and perspectives

In low viscosity discs, we find that Jupiter and Saturn are never closer than the 2:1 MMR and both planets migrate inwards. We firstly conclude that the Grand Tack scenario is not possible in such discs. When ice giants are added into these discs, systems are often unstable due to the lack of dissipation around the planets. Nevertheless, we find some resonant chains possible, all of which maintaining Jupiter and Saturn in the 2:1 MMR and with significant eccentricities (similar to Clement et al. 2021). Additionally, adding the ice giants stops the inward migration of the four giant planets, which can help keeping them from migrating to close to the Sun. From these resonant chains, we aim to reproduce the Solar System after a global instability phase as in the Nice Model. We find

† We consider the two ice giants to be interchangeable and therefore name them according to their final radial order.

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that it is possible, but at present the likelihood remains lower than in previous Nice Model studies. The conditions (timing/order) of capture in MMR and the morphology of planetesimal disc are critical and can allow for a wide variety of scenarii. This makes it much harder to connect the present configuration with the original state of the system. Therefore, further exploration in the instability phase is the subject of on-going work.

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