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MIGRATION OF ACCRETING GIANT PLANETS

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Abstract. We present the results of 2D hydro simulations of giant planets in proto-planetary discs, which accrete gas at a more or less high rate. First, starting from a solid core of 20 Earth masses, we show that as soon as the runaway accretion of gas turns on, the planet is saved from type I migration : the gap opening mass is reached before the planet is lost into its host star. Furthermore, gas accretion helps opening the gap in low mass discs. Consequently, if the accretion rate is limited to the disc supply, then the planet is already inside a gap and in type II migration.

We further show that the type II migration of a Jupiter mass planet actually depends on its accretion rate. Only when the accretion is high do we retrieve the classical picture where no gas crosses the gap and the planet follows the disc spreading.

These results impact our understanding of planet migration and planet population synthesis models.

The e-poster presenting these results in French can be found here :
L'e-poster présentant ces résultats en français est disponible à cette adresse :
`http://sf2a.eu/semaine-sf2a/2016/posterpdfs/156_179_49.pdf`.

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1 Introduction

In this e-poster, we present preliminary results relative to the problem of the migration of growing giant planets. Planetary migration is a phenomenon that changes the orbital radius of planets by gravitational interactions with the gaseous proto-planetary disc in which they form. Small planets are fully embedded in the disc, and subject to the *type I migration.* The typical speed of type I migration is inversely proportional to the mass of the planet, hence it can be extremely fast (few thousands of orbits) for planet of several tens of Earth masses. Giant planets (above typically $100 - 300$ Earth masses) in contrast open a gap in the disc profile, and are then driven by the disc, in so-called *type II migration*, generally slower. In the standard core-accretion model, a giant planet must grow from 0 to its final mass, and therefore experience type I migration as it grows, until it opens a gap. As a consequence, there is a significant risk that giant planets should be lost before having a chance of transitionning to the type II migration regime.

In section 2, we show that a giant planet should open a gap before being lost inside its host star by type I migration, provided it accretes gas in the runaway regime. In section 3, we study the subsequent type II migration of a giant planet, still in the runaway regime of accretion.

2 Type I – type II migration transition

Type I migration is directed inwards in standard isothermal discs (Ward 1997; Tanaka et al. 2002), but can be outwards when thermal effects are taken into account (e.g. Kley & Crida 2008; Kley et al. 2009). More precisely, this is due to the corotation torque, and requires specific conditions for the latter not to saturate, that is to vanish after a few libration periods in the horseshoe region. Paardekooper et al. (2011) provide a

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formula for the total torque felt by a planet which takes all these effects into account, and has been confirmed by 3D simulations Lega et al. (2014, 2015) (see Baruteau et al. 2014, for a complete review). From this, Bitsch et al. (2013, 2014a,b) have derived migration maps, in which the torque felt by a planet is shown as a function of the planetary mass and the distance to the star. These maps reveal the presence of an island of outward migration (at and beyond the snowline), which never goes above 30 Earth masses, and in most disks does not reach 20 Earth masses. Therefore, the too fast type I migration problem can be solved for giant planet cores, but remains open as soon as the mass exceeds $20 - 30M_\oplus$, where the corotation torque saturates.

Beyond this mass, there is a competition between accretion and migration to reach the gap opening mass (Crida et al. 2006) before having migrated inwards too much. We have performed 2D numerical simulations using the FARGO-2D1D code (Crida et al. 2007), with an isothermal equation of state (the thermal part of the corotation torque is therefore zero). The resolution is $dr/r = 0.01 = d\theta$. The aspect ratio of the disc is $h = H/r = 0.05$, uniform, and the viscosity is given by the Shakura & Sunyaev (1973) prescription : $\nu = \alpha H^2\Omega$ with $\alpha = 10^{-3}$. The planet starts at $r = 10$ with a mass of $20M_\oplus$, and is let free to migrate, while accreting gas. Gas accretion is performed using Kley (1999) recipe, caped by the accretion rate in runaway growth given by Machida et al. (2010, eq. (11)). The initial surface density of the gas disc is always of the form $\Sigma(r) = \Sigma_0 \times (L/r)^{-s}$ (where L is the length unit), and we try various values of Σ_0 because the migration speed is proportional to the surface density of the disc. Here, we choose $s = 1$ because with this slope of the density profile, the viscous spreading of the disc, and hence the type II migration should be very slow (see next section).

The result is shown in figure 1. In type II migration's conditions, our planets follow an almost vertical line, because accretion become much faster than migration. Whatever Σ_0, that is whatever the type I migration speed, the planets always transit to type II migration when they reach the gap opening mass (marked by the grey line). In all our simulations, the planets avoid migrating too close to their central star. In the most massive disk, though, the positive feedback on the migration provided by the partial opening of the gap (Masset & Papaloizou 2003) drives the planet to a semi-major axis only 30% from where it started its runaway accretion. Nonetheless, we can conclude that in general, the migration and the runaway accretion timescales are comparable (they both scale with Σ). Passing from the mass above which the corotation torque saturates to the mass above which a gap is open by the planet can be done with type I migration only reducing the semi major axis by a factor 2 (more in massive discs, less in light discs).

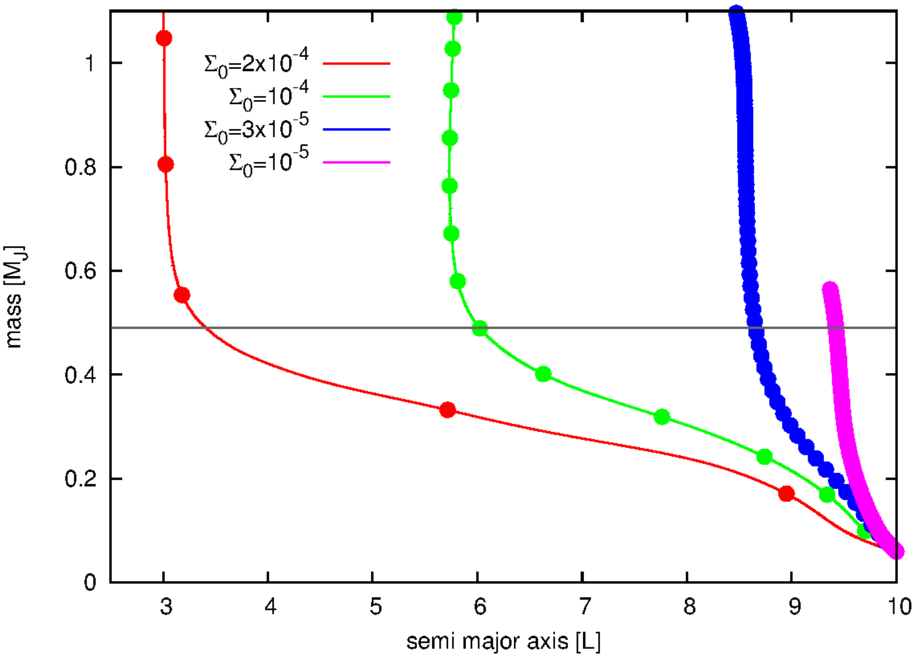

Fig. 1. Path of giant planets in the semi-major-axis versus mass plane, as they freely migrate while in runaway gas accretion. On each curve, a dot is placed every 1000 orbits at $r = 1$. Horizontal grey line : gap opening mass, which also marks the transition between the fast type I and the slow type II migration.

3 Type II migration of accreting giant planets

We now consider planets of Jupiter mass (that is a thousandth of the mass of the central star). In our simulations, they are first left on a fixed orbit for 200 orbits, to give them time to open a gap. They are then released free to migrate in type II migration. In standard type II migration the planets should be driven by the disc and follow its viscous evolution (Lin & Papaloizou 1986). However, it has been argued that some gas could pass through the gap, allowing the planet to decouple from the disc (e.g. Crida & Morbidelli 2007; Dürmann & Kley 2015). To test this, we change the slope of the power law of the gas profile s. Indeed, the viscous torque is $T_\nu = 3\pi\nu\Sigma r^2\Omega \propto r^{1-s}$. Hence, if $s < 1$, T_ν increases with r, and an elementary ring loses more angular momentum to its outer neighbour than it gains from its inner neighbour ; the gas drifts inwards. Conversely, if $s > 1$, the gas dirfts outwards. Therefore, one expects the type II migration to be directed inwards with $s = 0$, outwards with $s = 2$, and to be negligible with $s = 1$, as was the case in previous section.

The migration of the planets after release is shown in figure 2. Red curves correspond to the cases with $s = 0$, green to $s = 1$, and blue to $s = 2$. When the planets do not accrete (solid curves), they all end up migrating inwards. Thus, they must decouple from the disc, and gas is crossing the gap from the inner disc to the outer disc in the $s = 2$ case.

The dashed curves correspond to different accretion rates, using our smoothed version of Kley (1999) recipe, described hereafter. Within $0.8\,r_H$ of the planet (where r_H is the Hill radius), gas is removed from the disc and added to the planet mass. More precisely, in a time step dt, a fraction $f(d) \times dt$ of the gas located at a distance d from the planet is accreted, where $f(d)$ is given by :

$$f(d) = K \times \begin{cases} 1 & \text{if} \quad d < 0.3\,r_H \ , \\ \cos^2\left(\pi\left(\frac{d}{r_H} - 0.3\right)\right) & \text{if} \quad 0.3\,r_H < d \ . \end{cases} \tag{3.1}$$

The coefficient K is 1 for the long dashed curves, and 10 for the dotted curves (and 0 for the solid curves). Convergence is reached in the $s = 0$ (red) case : the migration rate is the same whether $K = 1$ of $K = 10$. A natural interpretation of this is that no gas is passing through the gap, it is all accreted.

In the other two cases, the more the planet accretes, the less it migrates inwards (or the more it migrates outwards). In particular, in the $s = 2$ case (blue), outwards migration is only sustained with $K = 10$. We interpret this as $K = 10$ being sufficient for no gas from the inner disc to reach the outer disc and refill it. As the outer disc keeps spreading outwards, it empties and the planet feels a weaker negative torque from it. It's torque balance remains positive (thanks to the inner disc) and it migrates outwards, pushed by the spreading of the outer disc.

4 Conclusions

In summary, we have first shown that growing giant planet should open a gap and therefore transition from type I to type II migration, before being lost into their central star. This holds even if their type I migration changes their orbital radius by more than the width of the gap during this process, as illustrated by the 2 left curves of figure 1. This result is developed in a peer review article (Crida & Bitsch 2016, in press).

Then, we have found that the accretion of gas by a gap opening giant planet influences dramatically its type II migration. This desserves a further, more complete study, and will be the topic of a forthcoming paper.

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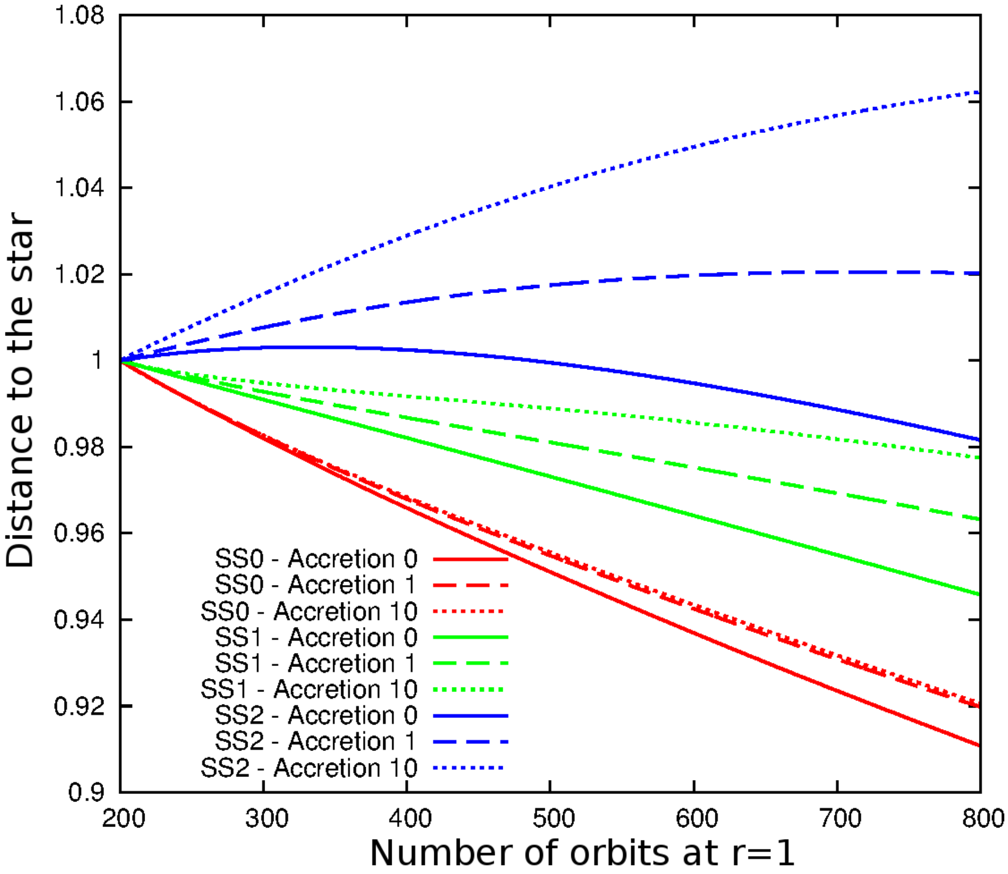

Fig. 2. Semi major axis as a function of time for Jupiter mass planets released after 200 orbits in a disc of initial profile of the density slope $s = 0, 1, 2$ (red, green, blue respectively). The planets accrete in an orbit the fraction of the gas located at a distance d given by $f(d)$ with $K = 0$ (no accretion, solid curves), $K = 1$ (long dashed curves), or $K = 10$ (dotted curves).

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