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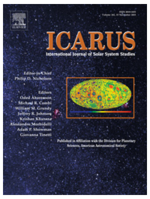

Runaway gas accretion and gap opening versus type I migration

A. Crida[a,b,*], B. Bitsch[c]

[a] Laboratoire Lagrange (UMR7293), Université Côte d'Azur / Observatoire de la Côte d'Azur, Boulevard de lObservatoire, CS 34229, 06300 Nice, France
[b] Institut Universitaire de France, 103 Boulevard Saint-Michel, 75005 Paris, France
[c] Lund Observatory, Department of Astronomy and Theoretical Physics, Lund University, Box 43, 22100 Lund, Sweden

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ABSTRACT

Growing planets interact with their natal protoplanetary disc, which exerts a torque onto them allowing them to migrate in the disc. Small mass planets do not affect the gas profile and migrate in the fast type-I migration. Although type-I migration can be directed outwards for planets smaller than $20 - 30 M_\oplus$ in some regions of the disc, planets above this mass should be lost into the central star long before the disc disperses. Massive planets push away material from their orbit and open a gap. They subsequently migrate in the slower, type II migration, which could save them from migrating all the way to the star. Hence, growing giant planets can be saved if and only if they can reach the gap opening mass, because this extends their migration timescale, allowing them to eventually survive at large orbits until the disc itself disperses.

However, most of the previous studies only measured the torques on planets with fixed masses and orbits to determine the migration rate. Additionally, the transition between type-I and type-II migration itself is not well studied, especially when taking the growth mechanism of rapid gas accretion from the surrounding disc into account. Here we use isothermal 2D disc simulations with FARGO-2D1D to study the migration behaviour of gas accreting protoplanets in discs. We find that migrating giant planets always open gaps in the disc. We further show analytically and numerically that in the runaway gas accretion regime, the growth time-scale is comparable to the type-I migration time-scale, indicating that growing planets will reach gap opening masses before migrating all the way to the central star in type-I migration if the disc is not extremely viscous and/or thick. An accretion rate limited to the radial gas flow in the disc, in contrast, is not fast enough. When gas accretion by the planet is taken into account, the gap opening process is accelerated because the planet accretes material originating from its horseshoe region. This allows an accreting planet to transition to type-II migration before being lost even if gas fails to be provided for a rapid enough growth and the classical gap opening mass is not reached.

1. Introduction

Planets form in proto-planetary discs. For the terrestrial planets of the solar system, only Moon to Mars sized embryos need to be formed in the proto-solar nebula; the final assembly of Venus and the Earth is thought to take place after the gas dispersal, through giant impacts among these embryos and leftover planetesimals (Jacobson et al., 2014; Kleine et al., 2009; Raymond et al., 2014). In contrast, giant planets must have acquired their final mass while gas was still present, as they are mostly composed of this gas. In the core-accretion model (Pollack et al., 1996), the gaseous envelope is slowly accreted around a solid core of ~ 10 Earth masses. Hence, gas giants must experience planet-disc interactions from the mass of an embryo all the way to that of Jupiter. A result of these interactions is planetary migration, which modifies the orbital radius of a planet, and generally moves it closer to the central star.

Giant planets open a gap around their orbit, separating the disc between an inner and an outer disc (Lin and Papaloizou, 1986a). In typical proto-planetary discs, this happens for planets more massive than Saturn or Jupiter (Crida et al., 2006). Once a gap is open, the planet should be locked between the inner and outer disc, and follow the viscous evolution of the proto-planetary disc, that is in general a slow accretion towards the central star (Lin and Papaloizou, 1986b; Nelson et al., 2000). This is called type II migration, and could explain the semi-major axis distribution of giant exoplanets (e.g. Lin et al., 1996), especially when photo-evaporation of the protoplanetary disc is taken into account

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[*] Corresponding author.
E-mail addresses: crida@oca.eu, aurelien.crida@oca.eu (A. Crida).

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(Alexander and Pascucci, 2012). It should be noted that the above description is ideal, and in reality a planet can decouple more or less from the disc evolution (Crida and Morbidelli, 2007; Dürmann and Kley, 2015), and some gas can pass through the gap (Lubow and D'Angelo, 2006). Despite these recent developments, the global picture that single gap opening planets migrate slowly and roughly *together with* the disc still holds.

In contrast, smaller planets – which do not perturb significantly the density profile of the disc – migrate *with respect to* the disc, in the so-called type I migration regime (Ward, 1997). In this regime, the migration rate is proportional to the planet mass. Hence, type I migration is not a big issue for the embryos of the terrestrial planets, but has always been an issue for growing giant planets: accreting a gaseous envelope should take way longer for their solid cores than migrating all the way into their host star (the typical migration time-scale for a 30 Earth mass body is only 10, 000 orbits). In fact, the first planet population synthesis models (Alibert et al., 2005; Benz et al., 2008; Ida and Lin, 2008; Mordasini et al., 2009) had to decrease the efficiency of type I migration by a factor 100 at least, if they wanted planets to survive.

In the past decade, huge progress has been made on type I migration, mainly relative to the corotation torque (see Baruteau et al., 2014, for a complete review). It has been shown that this torque can be positive, and overcome the classical, negative, differential Lindblad torque when the disc is not isothermal (Baruteau and Masset, 2008; Kley et al., 2009; Kley and Crida, 2008; Paardekooper and Mellema, 2006). Typically, this is efficient for planets in the $5-30M_\oplus$ range, in the inner regions of the disc, where the radial gradient of entropy is steep (ex: at opacity transitions). An analytical formula for the torque felt by a planet in type I migration has been found by Paardekooper et al. (2011) based on 2D numerical simulation, and confirmed in 3D radiative numerical simulations by Bitsch and Kley (2011) and more recently by Lega et al. (2015) who included stellar irradiation. Combined with an accurate description of the temperature and density profiles of the protoplanetary disc and its evolution, this allows to produce migration maps, where the torque felt by a planet is given as a function of its mass and position in the disc (Baillié et al., 2016; Bitsch et al., 2013, 2014a,b). In such maps, it appears possible to block a planet at a zero-torque radius, where it can grow slowly.

However, above a critical mass $M_{\rm crit}$, the corotation torque always saturates and vanishes. In general $M_{\rm crit} \approx 20M_\oplus$, depending on the opacity, density and viscosity of the disc. Therefore, the too fast type I migration problem is solved only below $M_{\rm crit}$. As $M_{\rm crit}$ is 5 to 10 times smaller than the gap opening mass, the question of the fast inwards migration of giant planets, as they grow from $M_{\rm crit}$ until they open a gap, remains open. In this paper, we address this critical question (and only this question). We study in which conditions a growing giant planet can open a gap before type I migration drives it all the way into its host star.

After having presented our set-up, code and units in Section 2, we first study briefly the opening of a gap by a *migrating* giant planet in Section 3. This study is necessary because Malik et al. (2015) recently suggested that giant planets would not be able to open their gap if they are migrating too fast. More precisely, they argue in favour of Hourigan and Ward (1984) who stated that if the planet crosses its corotation region faster than a gap opens, the gap never opens and the planet therefore remains in type I migration. If this is true, there is no hope for a giant planet to ever open a gap when its grows past $M_{\rm crit}$. In this case, the survival of giant planets would become a puzzle because they should never leave the type I migration regime. We show in contrast that a Jupiter mass planet does open a gap in about a hundred orbits, even if it migrates fast.

Second, we compare the growth and migration time-scales in Section 4. We show analytically and with numerical simulations that once a $20\,M_\oplus$ core starts its runaway gas accretion, it should reach the gap opening mass before its semi-major axis is dramatically reduced. Finally, one may worry that the theoretical runaway accretion rate cannot be sustained if the disk can not provide gas fast enough. However, we show in Section 5 that if this occurs, then the planet has already opened a gap because all the gas in its horseshoe region has spread to the accretion streams. Consequently, once the runaway accretion of gas starts, nothing prevents the opening of a gap by the growing giant planet. After a discussion in Section 6, we summarize our findings in Section 7.

2. Units and simulations set-up

In this paper, all our simulations are performed with the FARGO-2D1D code (Crida et al., 2007), which is a 2D grid code in polar $(r-\theta)$ coordinates. The resolution is always $dr/r = 0.01 = d\theta$, unless specified otherwise. Far from the planet, the standard 2D grid is replaced by a 1D grid, assuming azimuthal symmetry, allowing to model the viscous spreading of the disc. This is crucial for an accurate modelization of type II migration, but not necessary for a study of type I migration. Even if our focus here is not type II migration, but the transition into type II migration, we choose to use this code given the negligible computing cost of the 1D grid.

Our units are L as the arbitrary length unit (generally the initial orbital radius of the planet), the mass of the central star M_* as the mass unit, and we set the gravitational constant $G = 1$ so that an orbital period at L is given by $P_L = 2\pi T$ with $T = \sqrt{L^3/GM_*}$ the time unit.

The equation of state is locally isothermal, because we focus on cases where the thermal part of the corotation torque would be saturated. The aspect ratio is always uniform (no flaring) with the usual value $h = H/r = 0.05$, so that the sound speed is given by $c_s = \frac{0.05}{\sqrt{r/L}}\,(L/T)$. Unless stated otherwise, the gas viscosity is given by Shakura and Sunyaev (1973)'s prescription, with a rather standard value of $\alpha = 10^{-3}$. With this setting, a Jupiter mass planet (that is: a planet whose mass is $M_J = 10^{-3}M_*$, or mass ratio to the star is $q = 10^{-3}$) has a gap opening parameter as defined by Crida et al. (2006) of $2/3 < 1$, so we expect this planet to open a gap. The threshold for gap opening according to this criterion (that is: the gas density in the middle of the gap should be 10% of the unperturbed gas density) is $0.436\,M_J$.

The initial surface density of the gas disc is always of the form $\Sigma(r) = \Sigma_0 \times (L/r)$. With such a slope of the surface density profile and an α-prescription for the viscosity in a non-flared disc, the viscous torque exerted by the disc inside any radius r on the disc outside r is independent of r. Hence, the viscous torque on any elementary ring is zero, and the disc is at equilibrium, with no radial viscous drift of the gas. Of course, at the inner (resp. outer) edge of the disc, there is no support from an inner (resp outer) disc and the gas will spread. This perturbation to the density profile will propagate inside the disc profile at the viscous rate. Nonetheless, for most of the times we will consider here, the disc around the planetary orbit should not spread, and type II migration is expected to be very slow.

The semi-major axis of the planet is noted a, and its orbital angular velocity is $\Omega = \sqrt{GM_*/a^3}$. The gravitational potential of the planet is smoothed using the usual so-called ϵ-smoothing, with $\epsilon = 0.6\,r_H$ where $r_H = (q/3)^{1/3}a$ is the Hill radius of the planet. The self-gravity of the gas disc is not taken into account. Whenever the torque exerted by the disc on the planet is computed, the region within $0.6\,r_H$ is excluded, using a smooth Fermi function, as prescribed by Crida et al. (2009).

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