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Gap opening by gas accretion and influence on planet populations

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Abstract

Giant planets grow and migrate in protoplanetary disks. Because they accrete gas from their horseshoe region until the latter is depleted, giant planets can open a gap before being lost into their central star by type I migration. A reduced type II migration is then necessary to limit the total amount of migration that a giant planet suffers during its formation.

1. Introduction

Planets form and migrate in gaseous proto-planetary discs. Giant planets open gaps in the disc above a critical mass $M_{\rm gap}$ of a few hundred Earth masses ; then, they follow the slow, so-called type II migration. Below $M_{\rm gap}$, planets are subject to the fast type I migration, whose timescale is much shorter than the disc lifetime for planets above $\sim 10M_\oplus$. Fortunatelly, the generally inwards type I migration can be directed outwards in some regions of the disk [6], allowing for planets to converge to an equilibrium radius of a few AUs [5]. However, this only works for a limited range of masses, below a critical mass $M_{\rm crit\,I} \approx 25\,M_\oplus$ [1, 4]. The range between ~ 25 and $\sim 100\,M_\oplus$ therefore appears critical in the growth of a giant planet.

Here, we solve this problem and show [3] (i) that giant planets actually accrete with the runaway growth rate until they open a gap and transition to type II migration (ii) that this accretion rate is fast enough for type I migration to be of limited amplitude between $M_{\rm crit\,I}$ and $M_{\rm gap}$.

We inquire how this better description of the growth and migration of a giant planet affects their final masses and orbital radius. We also explore the role of type II migration, which could be reduced in a so-called dead zone.

2. Gas accretion and gap opening

In most planet population synthesis models, the gas accretion rate of the giant planets does not follow the theoretical runaway growth rates given by 1D or 3D models of a giant planet embedded in a gas disk. Instead, the gas accretion rate of the planet is limited to the gas accretion rate of the disc onto the star. This is rather intuitive : the planet can not accrete more gas than is provided. But this omits that the planet has an easily accessible reservoir of gas to start with : the gas in its horesehoe region. Indeed, as soon as accretion starts, the gas separatrices of the horseshoe region are distorted and the gas next to them is eaten by the planet. The horseshoe region then spreads viscously (fast because it has a small radial extent) into the empty separatrix, where it is funnelled to the planet. Numerical simulations confirm that the accretion rate should not be limited until the horseshoe region is depleted (either by accretion, or by the gravitational torque of the planet). This has two crucial consequences.

2.1. Gas accretion vs type I migration

First of all, as long as the planet has not opened a gap, its accretion rate is the one given by runaway gas accretion models. This rate is proportional to the gas surface density, just like the type I migration rate. Therefore, the race between migration and accretion above $M_{\rm crit\,I}$ is fair. Whereas migration wins easily if the gas accretion is limited to the disk supply, we find (both numerically and analytically) that without this limitation, planets open a gap before type I migration makes their orbital radius shrink to zero. In fact the orbital radius is hardly divided by 3 in most cases. In particular, we checked that even a fast migrating planet can open a gap if massive enough ; the transition to type II migration then takes about 100 orbits.

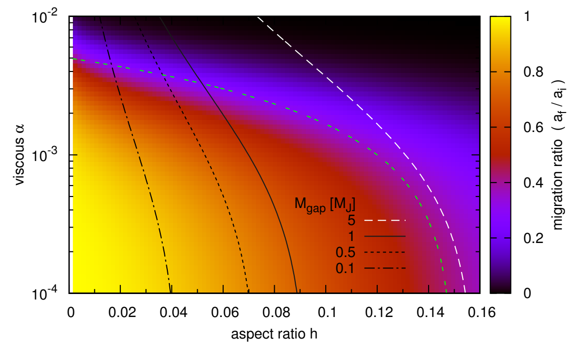

Figure 1: Color map : ratio of the initial to final semi major axis of a planet that migrates in type I migration while growing from 0 to the gap opening mass in the runaway regime. Black and white lines : contours of the gap opening mass $M_{\rm gap}$. Green double-dashed line : $\alpha = 0.005 - h/30$ (crude proxy for the $a_f/a_i = 0.4$ contour line).

More precisely, figure 1 shows as a color map the ratio of the initial to final orbital radius as a function of the disc parameters (aspect ratio and viscosity), for a planet migrating at the theoretical type I rate while accreting at the theoretical runaway growth rate upto a mass allowing for gap opening.

In summary, above $M_{\rm crit\,I}$, planets should migrate inwards fast in type I migration. But if they reached the critical mass to start their runaway gas accretion phase, migration doesn't win over accretion and a gap will be open before the planet is lost. Fortunately, the mass above which the runaway gas accretion start is of the same order as $M_{\rm crit\,I}$.

2.2. Final masses & orbits of giant planets

We have modified the planet formation model developped by [2] according to the above description. Specificaly, we now compute the amount of gas accreted by the planet, and remove this from the horseshoe region. This region is depleted both by this accretion and by the gravitationnal torque from the planet. When it is empty, the gas accretion rate of the planet is limited to 80% of the disk supply, and the migration is of pure type II.

As expected, this leads to slightly more massive giant planets, and allows to save giant planets from a fall into their host stars for a wider range of initial conditions. However, most planets still see their orbital radius divided by more than a factor 5 from their birth to their final position. Most of this migration is now coming from the type II phase.

Therefore, we have explored the case of low viscosity disks, mimicking stratified discs with an "active" upper layer and a "dead" midplane. In this case, we expect the type II migration to be very much slowed down. However, the type I migration is always inwards (saturation of the corotation torque) ; but the dynamical coroation torque [7] limits its amplitude. This allows the total migration of the planets to be limited.

3. Summary and Conclusion

We have studied the competition between gas accretion and migration of growing giant planets. Numerical simulations and analytical calculations show that planets should be able to open a gap before type I migration drives them into their host star.

We have explored the influence of this result on a model of planet formation, and shown its importance. We have further explored the influence of stratified disk model, using a schematic view of the migration in such a disk. Indeed in the layered discs, forming giant planets seem to only experience limited migration and can thus form very close to their final position. These results will be presented.

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