SF2A 2011
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PLANETARY MIGRATION AND ACCRETION

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Abstract. In this plenary session talk, I review some of the most important recent progresses in planetary science. I focus here on two aspects linked to planetary formation.

In section 2, I present the issue of planetary migration of type I. After an introduction to planet-disk interactions, I present the differential Lindblad torque, responsible for a too fast inward migration of terrestrial planets. Then, the corotation torque is presented. It is shown that the total torque is positive in the inner regions of the disk, and negative in the outer regions, leading to a convergence of terrestrial planets to an equilibrium radius.

In section 3, I present a new scenario for the formation of Saturn's rings and satellites. New results suggest that the rings were initially very massive, made of pieces of the icy mantle of differentiated satellite that migrated into Saturn at the time of solar system formation. These rings then spread viscously, and reach the observed mass and density in about 4 Gyrs. As a by-product of this spreading, all the satellites inside the orbit of Titan form beyond the Roche limit and then migrate to their present position.

Keywords: planetary formation, planetary migration, protoplanetary disks, planet-disk interactions, planet: Saturn, Saturn: rings

1 Introduction

Planetary formation takes place in proto-planetary disks. These disks of gas and dust around young stars have typically an aspect ratio of the order of $H/r \approx 0.05$, which translates into a temperature of the order of $T = 150\,\mathrm{K} \times (1\ \mathrm{AU}/r)$, where r is the distance to the central star and H the scale height of the disk. These disks spread, and accrete into the star, and finally vanish in a few million years. Meanwhile, in the proto-planetary disks, the heavy elements condensate and agglomerate to form planets. From micro-metric grains to giant planets, this is 14 orders of magnitude to grow!

It is generally considered that this takes place at first in 5 steps:

- Condensation to micrometer grains of solids,
- Sedimentation of the grains onto the mid-plane,
- Aggregation up to mm-cm dust packets,
- Formation of planetesimals of a few km,
- Formation of embryos of more than a few thousand km.

Then, if an embryo is massive enough (about 10 Earth masses), it accretes a gaseous envelope, that slowly grows and cools. At some point, the hydrostatic equilibrium of the envelope is not possible anymore, and it collapses. This leads to the formation of a giant gaseous planet, in the most accepted model by Pollack et al. (1996). So, planet formation must take place inside the gas disk. In this review, I won't discuss the complex processes of planet formation, but I present the interactions between a planet or an embryo and the gaseous protoplanetary disk. The latest results on planetary migration are shown, and the perspectives are drawn.

In section 3, I will also discuss recent results about the formation of Saturn's rings and satellites system, in which migration and accretion are the key.

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2 Planetary migration

The gravity of a planet perturbs the trajectory of the gas particles. This leads to the formation of a one armed spiral wave, the *wake* (see Fig. 1, left panel). Due to the Keplerian rotation, the wave is leading the planet in the inner part of the disk, and trailing behind the planet in the outer disk.

This wave is a pressure-supported, density wave. It represents a mass excess with respect to the unperturbed disk. Therefore, the wave and the planet gravitationally attract each other. This results in a torque and orbital angular momentum transfer. The basic result is that the inner disk gives angular momentum to the planet, and the planet gives angular momentum to the outer disk.

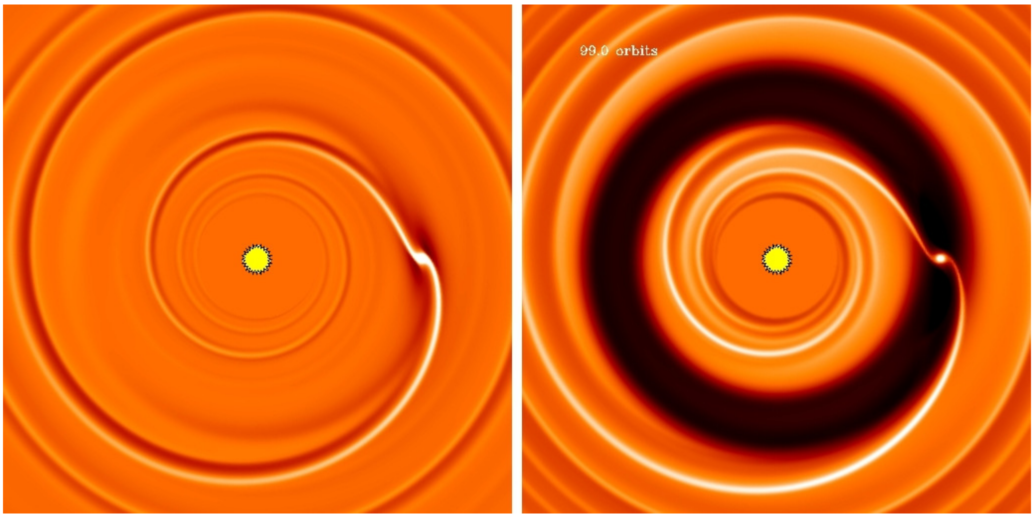

Fig. 1. Examples of planet-disk interaction. The star is in the center of the square, and the planet is in the middle of the white blob on the right. The rotation is counter-clockwise. The color represents the gas density : light for high density, dark for low density. Images by F. Masset, modified by A. Crida. **Left:** Wake created by a terrestrial planet. **Right:** Gap opened by a giant planet.

2.1 Type II migration

If the planetary torque is massive enough (case of a giant planet), this results in the opening of a gap around the planetary orbit (Lin & Papaloizou 1986a; Takeuchi et al. 1996; Crida et al. 2006) : the inner disk is repelled inward, and the outer disk outward (see right panel of figure 1).

In this case, the planet is locked in the gap, and follows the viscous evolution of the disk. This drives the planet towards the central star on a viscous time-scale (of the order of a million years). This is called *type II migration* (Lin & Papaloizou 1986b, see also Crida & Morbidelli (2007)).

This is consistent with the observation of hot Jupiters : giant planets observed within 0.1 AU from their host star, where they couldn't form because there is not enough solid material to form a massive core.

2.2 Type I migration

If the planet is not massive enough, the profile of the disk is not changed, and the perturbation remains linear (figure 1, left panel). Nonetheless, angular momentum is exchanged, and the planet should migrate with respect to the gas disk. This is *type I migration* (Ward 1997).

2.2.1 Differential Lindblad torque

In the linear case, Ward (1986) has demonstrated that the torque from the outer disk always dominates that from the inner disk. The total torque felt by the planet, called the *differential Lindblad torque*, is thus negative. It reads (Tanaka et al. 2002) :

$$\Gamma_{dLt} = -(3.2 + 1.468\alpha)\Gamma_0 \tag{2.1}$$

where $\alpha = \mathrm{d}\log\Sigma/\mathrm{d}\log r$, Σ being the surface density of the gas disk, and

$$\Gamma_0 = \left(\frac{M_p}{M_*}\right)^2 \Sigma\, {r_p}^4\, {\Omega_p}^2 \left(\frac{H}{r}\right)^{-2} \tag{2.2}$$

where M_p is the mass of the planet, M_* the mass of the central star, r_p is the radius of the planetary orbit, and Ω_p is the angular velocity of the planet.

Application The migration speed is proportional to the planet mass. As a consequence, an Earth mass planet in a typical protoplanetary disk at 1 AU is lost into the Sun in about 2×10^5 years. This is a problem : no planet should survive !

2.2.2 Corotation torque

Not only the inner and outer disk should be considered, but also the horseshoe region. As shown in the left panel of figure 2, it is the region around the planetary orbit where gas particles have a horseshoe-shaped orbit, well-known in the restricted three-body problem.

Gas particles on these orbits on average co-rotate around the central star with the planet. Particles slightly outside the planetary orbit are caught up by the planet. The planet being behind them, it exerts a negative torque on them. Thus, these particles are sent onto a smaller orbit, inside the planetary orbit. Then, they orbit around the star faster than the planet does. In the frame rotating with the planet, they make a U-turn. They eventually catch up with the planet, that accelerates them and sends them back on an outer orbit, in an other U-turn. This results in angular momentum exchange, and a torque on the planet, called the *corotation torque* or more precisely the *horseshoe drag* (Paardekooper & Papaloizou 2009, and references therein).

Assume that the radial entropy gradient is negative. Then at the U-turn leading the planet, colder gas is sent from outside to inside the planetary orbit. And behind the planet, gas from the inner hotter region is sent to the colder outer region. Pressure equilibration after the U-turn leads to density variation, to balance the temperature difference. Thus, the hot plume trailing behind the planet becomes under-dense, while the cold plume leading the planet is over-dense. The result is a strong positive torque in non isothermal disks, first discovered by Paardekooper & Mellema (2006).

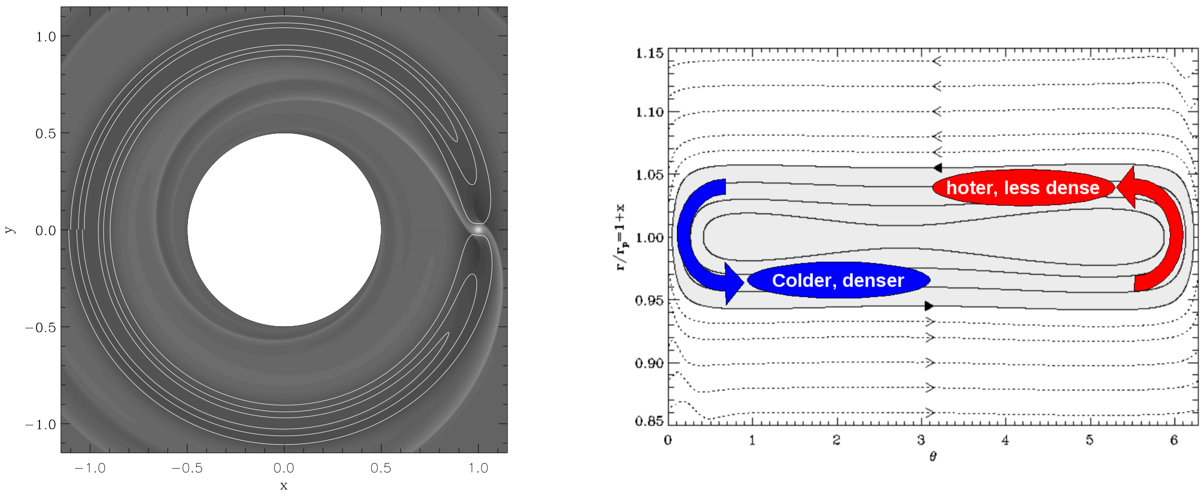

Fig. 2. Left: Horseshoe-shaped orbits, seen in Cartesian coordinates $x - y$. **Right:** The horseshoe orbits in the $\theta - r$ plane ; the U-turns of cold and hot gas are shown on the left and right, respectively. Images by F. Masset, modified by A. Crida.

This effect has been studied by many authors, as is appears to be a possible solution to the too fast inward type I migration problem (e.g. Baruteau & Masset 2008; Kley & Crida 2008; Masset & Casoli 2009). Finally, Paardekooper et al. (2010) have derived an expression for the type I torque, that takes the thermal part of the corotation torque into account :

$$\gamma\Gamma = -(0.9 + \alpha + 1.7\beta - 7.9\xi/\gamma)\Gamma_0 \tag{2.3}$$

where γ is the adiabatic index, $\beta = \mathrm{d}\log T/\mathrm{d}\log r$, and $\xi = \beta - (\gamma - 1)\alpha$.

2.2.3 Saturation of the corotation torque

The "thermal corotation torque" described above requires some conditions. First, the disk should not be completely adiabatic ; otherwise, after a few libration periods, the horseshoe region will be well-mixed, and uniformly warm. No more hot/cold plume, no more positive torque. This is called the *saturation* of the corotation torque (see Paardekooper et al. 2011). It cancels the positive torque. To prevent saturation, the initial entropy gradient needs to be restored (e.g. Kley & Crida 2008).

On the other hand, the cooling/heating should not be too fast ; otherwise by the time gas particles make a U-turn, they reach the local temperature at their destination radius. The disk should not be locally isothermal either.

These conditions can be summed up in conditions on the cooling time, compared to the libration and U-turn times :

$$\tau_{\mathrm{U-turn}} < \tau_{\mathrm{cooling}} < \tau_{\mathrm{libration}} \ . \tag{2.4}$$

2.2.4 Saving the planets

In the inner regions of the protoplanetary disk, the density is high, the opacity too, and the cooling time is therefore relatively long, at least longer than the U-turn time. Migration should be directed outwards.

In the outer parts of the disk, the opacity is low, and the cooling efficient. The gas is almost locally isothermal, and the cooling time is smaller than the U-turn time. Migration should be directed inwards.

In the end, there should be a convergence radius, where planets or embryos should gather. It could be of the order a few AUs, according to some preliminary works by Mordasini et al., who even find 2 such equilibrium radii, because the opacity is not a monotonic function of r (private communication).

In conclusion, it seems that the problem of the dramatic loss of terrestrial planets by type I migration is solved, thanks to the theoretical breakthroughs of the past five years.

There seems to be locations in the disk where terrestrial planets gather. These equilibrium radii are most likely sweet spots for the fast formation of massive embryos, the future cores of the giant planets. However, the interactions between these embryos should be taken into account, and the influence of the mass of the planet on the equilibrium radius should be inquired. In the coming years, research in planetary migration and formation will address this question. It should lead to a better understanding of the formation of giant planets, with interesting applications to the Solar System and exoplanetary systems.

3 Formation of Saturn's system

Recent articles published in 2010 have changed our understanding of the system of Saturn. Put together, these new results draw a global picture and a completely new scenario for the formation of Saturn's rings and satellites. Of course, some caveats still need to be addressed, but this is very promising.

3.1 Formation of massive, icy rings

At the end of their formation, giant planets are surrounded by a circum-planetary disk of gas and dust, like a miniature proto-planetary disk. In this disk, planetary formation takes place, leading to the formation of a satellites system around the planet. Due to type I migration, many satellites are lost into the central planet (Canup & Ward 2002). It is assumed here that type I migration is directed inwards in the circum-planetary disk.

Canup (2010) suggests that the last massive, differentiated satellite that migrated towards Saturn was "peeled off" by the tides of Saturn (see also Crida & Charnoz 2010). Indeed, the Roche radius for ice is located at about 140 000 km from Saturn, while the Roche radius for silicates is at about 90 000 km. Canup suggests that this was the radius of Saturn at the time of its formation. Consequently, a differentiated satellite with an icy mantle and a silicate core (like Titan) that migrates inside 140 000 km, would lose its mantle, while its core would fall into Saturn, as shown in numerical simulations.

The final result is a massive ring of ice blocks between Saturn and the Roche limit, and nothing else between this ring and Titan... This scenario explains the composition of the rings (amazingly more than 90% water ice).

3.2 Viscous spreading of massive rings

Salmon et al. (2010) have studied the viscous spreading of Saturn's rings. Applying Daisaka et al. (2001)'s prescription for the viscosity in (non) self-gravitating disks, they find that the present rings could be as old as the Solar System. In fact, the more massive the rings are, the more viscous they are, and the faster they spread. Thus, whatever their initial mass, they should reach in less than 4 billion years a density profile such that their Toomre parameter Q is of the order of 2 everywhere. This corresponds quite well to the presently observed profile.

This result enables to bridge the gap between the massive rings formed in Canup's scenario 4.5 Gyrs ago, and the present rings.

3.3 Satellites formation from the viscous spreading the rings

As the rings spread, what happens to the material of the rings that flows beyond the Roche radius ? By definition of the Roche radius, it can form gravitational aggregates. Such aggregates migrate outwards (due to the positive torque from the inner disk, the rings). As they migrate outward, they also merge with each other, and grow, which increases their migration speed.

Charnoz et al. (2010) have shown that the small moons of Saturn, orbiting just outside the rings (namely Janus, Epimetheus, Pandora, Prometheus, and Atlas), formed this way. It is well reproduced by numerical simulations, and it explains at the same time their surface properties, composition, density, shape, orbital radii... As a consequence, they actually formed only a few to a hundred million years ago.

Charnoz et al. (2011) extend this result to all the satellites inside the orbit of Titan. Starting from massive rings as in section 3.1, it is possible to form the mid-sized moons (Rhea, Dione, Tethys, Enceladus, Mimas), in less than 3.5 Gyrs*. In fact, this would also explain the origin of the silicate cores of these bodies : chucks of silicates are likely to have been present in the rings at their formation. They would have formed gravitational aggregates, acquired an ice shell, and migrated through the rings. Some of them migrated outwards, and ended out of the rings, giving birth to the embryos of the mid-sized moons. Then they went on migrating outwards, accreting ice aggregates coming out of the rings.

3.4 Conclusion

This new scenario for the origin of Saturn's ring and satellite system could solve a long-standing mystery of planetary science. It provides the rings with an age, gives a satisfactory explanation for the composition of the rings, and their resistance to meteoritic pollution (in massive rings, the pollution is diluted). It also shows that many satellites of Saturn are actually much younger than the Solar System.

The idea of satellite formation from the spreading of a ring of solid particles beyond its outer edge at the Roche limit (a "tidal disk"), is particularly appealing, and could be applied to other planets. An analytical model has just been developed by Crida & Charnoz (2011). This field is going to be very active in the next years, improving our understanding of satellite formation in the Solar System.

A. Crida thanks the organizers of the "journées de la SF2A 2011", and the french national program of planetary science (PNP), for the invitation to present this review talk in plenary session.

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*This requires however that the tides of Saturn are about ten times more efficient than previously thought, but we have good reasons to believe that for Saturn, $Q = 1680$. See coming work by Lainey et al. and Mathis et al.

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