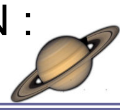
BEATING MIGRATION DURING GIANT PLANET FORMATION : A PLAUSIBLE SCENARIO



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Abstract :

Jupiter and Saturn raise two dynamical problems in the framework of formation and evolution of giant planets in protoplanetary disks. First, type I migration drives solid cores into the central star before they can reach the critical mass for runaway accretion of gas ; thus, giant planets should not exist. Second, an hypothetical giant planet in the disk would open a gap and suffer type II migration, which would drive it in the vicinity of the star on a viscous timescale ; this explains the presence of "hot" Jupiters, but evidently was not the case in our Solar System.

Here we propose a consistent view of giant planet formation that solves these two problems.

1) Stopping type I migration at a "planet trap".

A steep density jump in the radial profile of the gas disk stops type I migration and thus acts like a planet trap (Masset *et al.,* in prep.). Indeed, the corotation torque – exerted on the planet by the material in the horseshoe region – is strongly increased at a density jump and compensates the negative differential Lindblad torque (responsible for type I migration).

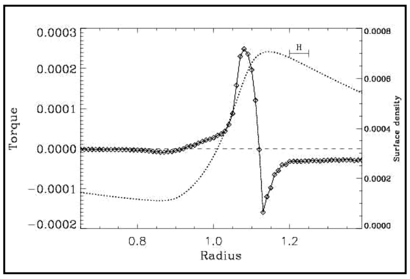

Figure 1 : Plain line : total torque felt by a planet as a function of its radial distance ; Dashed line : density profile (right y-scale). A stable equilibrium point appears at r≈1.12, which we call the trap.

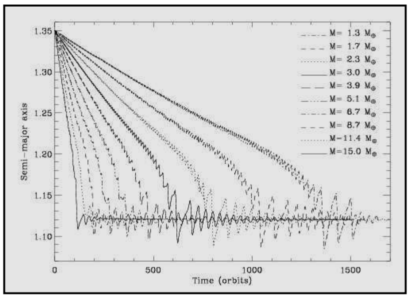

Figure 2 : Migration of several embryos of masses from 1.3 to 15 M_{earth}. They first suffer a rapid type I migration, and then are caught by the trap observed in Fig. 1.

Such density jumps are likely to exist in protoplanetary disks, for instance at the outer edge of the base of a jet, or the inner edge of a dead zone, *i.e.* at several A.U. from the central star.

2) Forming giant planets.

The accumulation of planetary embryos at the trap enhances the accretion rate. A giant core is likely to form at the trap on a relatively short timescale, and to remain there until it becomes a giant gaseous planet : **Jupiter**.

Jupiter then opens a gap in the disk and starts suffering type II migration, which is slower than the type I migration of most embryos.

Consequently, the embryos reach the outer edge of Jupiter's gap, which acts again as a planet trap. Thus, the formation of a new giant planet is boosted : **Saturn** appears.

The capture of embryos in outer mean motion resonances with Jupiter leads to the same result (Thommes *et al.*, 2005).

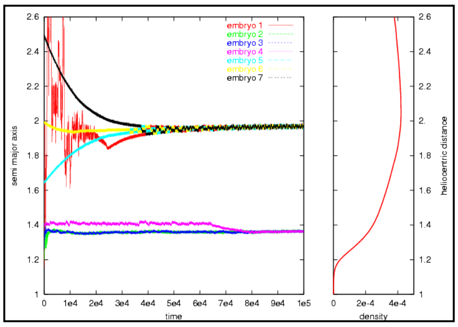

Figure 3 : Evolution of Earth-mass embryos initially distributed at the outer edge of Jupiter's gap. The gas density profile is shown on the right panel and does not evolve (Jupiter's orbit is here fixed). The evolutions of their semi-major axes are shown on the left panel. After migration or scattering by Jupiter, the embryos gather at stable points :

a ≈ 1.36 is the 8:5 resonance,

a ≈ 2 is the planet trap.

3) Preventing type II migration of the Jupiter-Saturn pair

Saturn is thus likely to form at the edge of Jupiter's gap and its gap can merge with Jupiter's one (see Figure 4) :

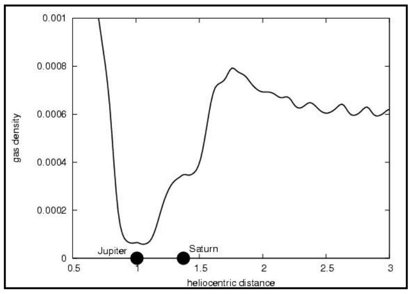

Figure 4 : Example of common gap opened byJupiter and Saturn.

Inside this common gap, the two planets can lock in mean motion resonance (most often 5:3, 8:5 or 3:2). Then, the migration process changes radically, and the migration of the pair may be reversed or halted, as illustrated in the following figure (Masset & Snellgrove, 2001).

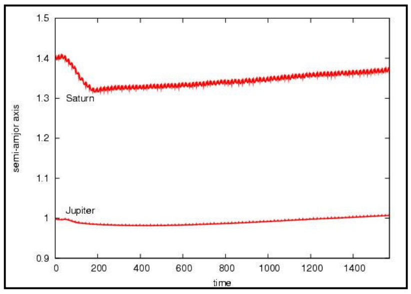

Figure 5 : Jupiter and Saturn's migration is reversed when they lock in 8:5 MMR.

When the gas disapears, the two planets orbit at several A.U. from the Sun, with $P_S/P_J < 2$, as required by a recent model on the origin of the current structure of the solar system (Tsiganis *et al.*, 2005 ; Morbidelli *et al.*, 2005) and of the Late Heavy Bombardment (Gomes *et al.*, 2005).

Conclusion :

This scenario provides a consistent view of the formation of the giant planets in the solar system during the disk phase.

It solves the problems raised by the type I migration of the protoplanetary cores and the type II migration of Jupiter. Moreover, it is consistent with recent models of the subsequent evolution of the planets in the remaining planetesimal disk. The individual steps of this process, here just outlined, are currently under deep investigation by our group.