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Pebble isolation and planetesimal formation by Super Earth planets

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Abstract

The constrains on the age and composition of the primordial bodies in the solar system require that the mixing stopped during the formation of Jupiter. The dust trap created by a 20 Earth mass embryo is proposed in several studies as an answer, but the timing is not fulfilled. Thanks to high-resolution simulations we show that a critical mass 3 times smaller is in fact sufficient, because the pebbles can stop inside the planet orbit. The growth towards Jupiter mass can be triggered by accretion of planetesimals, which form once the embryo is bigger than 20 Earth masses.

1. Introduction

The analysis of age, composition and isotope characteristic of primordial bodies of the solar system show that two distinct reservoirs exist within the protoplanetary disk. This dicotomy has appeared within less than 10^5 years, and is commonly explained by the formation of Jupiter. However, the stopping of the flux of solids requires a Jupiter core of 20 Earth masses (M_e) according to recent results ([3], [4]). The time needed to form such a core is still hardly compatible with the laboratory constrains. We present here a series of high resolution simulations where pebbles evolve in a disk containing a Jupiter embryo, to revisit this critical mass, and the effects on the distribution of pebbles in the disk.

2. Methods

We consider a 2D MMSN model of the disk, with background profiles of surface density and temperature in $\sigma_0(r) \propto (r/r_0)^{-1}$ and $T_0(r) \propto (r/r_0)^{-1/2}$, respectively. The reference radius is $r_0 = 5$ au. The gas has a cooling prescription in $[T - T_0(r)]/\tau_c$, with $\tau_c = 1000$ local periods, to allow dissipation of the heat generated by the shock waves. The pebbles are treated as a pressure-less fluid, fully coupled with the gas through the drag law proportional to the Stokes number $St = r_s \rho_s \sigma_g^{-1} \pi/2$. We use $St = 0.05$ at r_0, giving a radius of the pebbles r_s in the range $1.5 - 3$ cm depending on their composition ($\rho_s = 1 - 3\, g/cm^{-3}$). Gas and pebbles are evolved using the code RoSSBi ([1], [2]), which solves the Euler compressible equations on a polar grid using $(N_r,\ N_\theta) = (3072,\ 2048)$ cells for $1/3 < r < 2$ and $0 < \theta < 2\pi$. The planet orbit is evolved simultaneously, and migration is possible under the gravity exerted by the gas and the pebbles.

3. Stopping the flux of pebbles

3.1. Flux reduction in the inner disk

When the mass of the planet is in the range $8 - 10\, M_e$, the flux of pebbles is stopped for the inner parts of the disk. The left arm of the shock wave excited by the planet generates a trap, where the solids accumulate. The radial flux cancels, which avoids the pebbles to pass through and reach the inner parts of the disk. The location of this trap is around $r = 0.5\, r_0$ (see Fig. 1, top), and stays at this orbit for several thousands of disk orbits. The flux of pebbles from the outer parts of the disk is conserved, and the planet can keep growing by pebble accretion. This process has a strong impact on the explanation of the dicotomy in the composition of the meteoritic material and primordial bodies. The mixing through the disk can be stopped much earlier (few 10^5 years), because we show that the mass needed is $2 - 3$ times smaller than 20 M_e.

3.2. Flux reduction for the planet

When the planet grows to about 20 M_e, the pebble accretion onto the planet stops. The right arm of the shock carves the disk and generates a trap where the radial flux of solids reverses. This effect avoids the pebbles not only to reach the inner parts of the disk, but also the planet itself. The growth by accretion of solids stalls, which can explain the high probability to

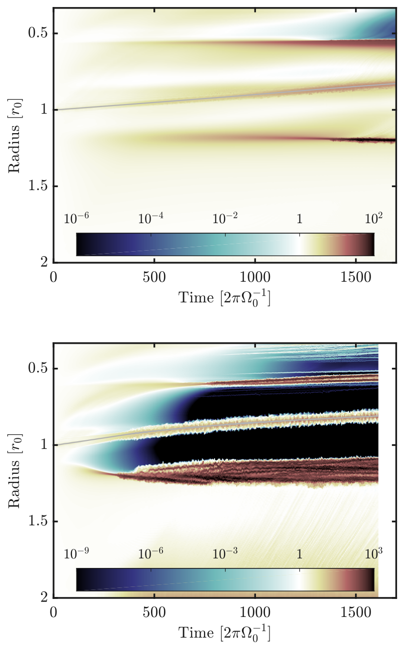

Figure 1: Time evolution of the pebble density for $M_p = 10\ M_e$ (top) and $M_p = 20\ M_e$ (bottom). The radial position of the planet is reported in gray line.

form Super Earth planets and to observe them in extrasolar systems. The location of this trap moves inward along the planet migration, which is still at work. Thus the region of accumulation of solids widen, in the region $1 < r < 1.2$ as seen of Fig. 1, bottom.

4. Planetesimal formation triggering

The accumulation of pebbles at the traps created by the planet creates a turbulent flow, where the formation of dust clumps is frequent (see Fig 2). These instable dust rings already observed in [1], contain several Earth masses in several solid-dominated eddies. This process is an alternative to the Streaming Instability to generate high dust-to-gas ratios in the disk, and is naturaly triggered by the planet whithin a short period of time, less than 5000 years. Under local gravitational instability, these clumps could form planetesimals and asteroids, which can decouple from the gas, and pass through the trap. The planet can then grow again by accretion of planetesimals, which is a recent promising senario to the formation of Jupiter.

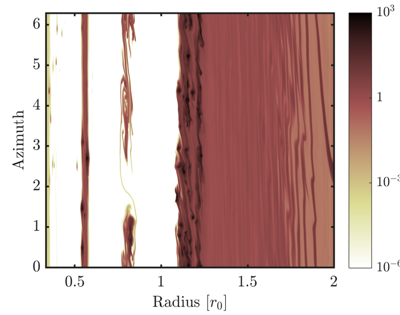

Figure 2: Pebble distribution in the disk after 1600 disk rotations (18×10^3 years) for a $M_p = 20\ M_e$ embryo.

5. Summary and Conclusions

The mass of the Jupiter embryo necessary to stop the mixing of solids with the inner solar system is in the range $8 - 10 M_e$. The date of this stopping can be much earlier than previously estimated, and fall whithin the laboratory constrains. In this case, the trap is located between the planet and the star, which allows the core to keep growing. When it reaches the classical $20\ M_e$, pebble accretion on the embryo stops, but the possible planetesimal formation triggered on the outer parts can help entering a phase of planetesimal accretion, and form Jupiter.

References

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