Giant planet formation via pebble accretion

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Abstract

In the standard model of core accretion, the formation of giant planets occurs by two main processes: first, a massive core is formed by the accretion of solid material; then, when this core exceeds a critical value (typically greater than 10 Earth masses) a gaseous runaway growth is triggered and the planet accretes big quantities of gas in a short period of time until the planet achieves its final mass. Thus, the formation of a massive core has to occur when the nebular gas is still available in the disk. This phenomenon imposes a strong time-scale constraint in giant planet formation due to the fact that the lifetimes of the observed protoplanetary disks are between 1 Myr and 10 Myr. The formation of massive cores before 10 Myr by accretion of big planetesimals (with radii >10 km) in the oligarchic growth regime is only possible in massive disks. However, planetesimal accretion rates significantly increase for small bodies, especially for pebbles which are strongly coupled with the gas. In this work, we study the formation of giant planets incorporating pebble accretion rates in our global model of planet formation.

Introduction

In the standard core accretion model the main question regarding giant planet formation is how to form massive cores before the dissipation of the protoplanetary disk. Ormel & Klahr (2010) and Lambrechts & Johansen (2012) demonstrated that small particles, often called *pebbles*, with Stoke number $S_t \lesssim 1$ are strong coupled to the gas and are very efficiently accreted by the planets. The main difference with planetesimal accretion is that pebbles can be accreted by the full Hill sphere of the planet while planetesimals can only be accreted by a fraction $\alpha^{1/2}\,R_H$, with $\alpha = \sqrt{R_c/R_H}$, being R_c the core radius of the planet. Thus, pebble accretion appears as a new alternative in the formation of giant planets.

Our model of planet formation

In a series of previous works (Guilera et al. 2010, 2011, 2014) we developed a model which calculates the formation of planets immersed in a protoplanetary disk that evolves in time. In this new work, we incorporate the pebble accretion rates given by Lambrechts & Johansen (2014) in order to study the formation of giant planets by pebble accretion. The main characteristics of our model are:

Planets

- solid cores grow by planetesimal accretion (in the oligarchic regime) or by pebble accretion,
- gas accretion and the thermodynamic state of the planet envelope are calculated solving the standard equations of stellar evolution.

The protoplanetary disk

- a gaseous component → α accretion disk + photoevaporation,
- a planetesimal population → evolves by 3 factors:
  - i- planetesimal accretion by the planets,
  - ii- planetesimal migration due to gas drag (3 regimes: Epstein, Stokes and quadratic),
  - iii- planetesimal collisional evolution.

Evolution of the disk

Gaseous component: a diffusion equation (+ photoevaporation) for the gas surface density Σ_g

$$\frac{\partial \Sigma_g}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}\left(\nu \Sigma_g R^{1/2}\right)\right] + \dot{\Sigma}_w(R)$$

Solid component: a continuity equation for the solid surface density Σ_p

$$\frac{\partial \Sigma_p}{\partial t} - \frac{1}{R}\frac{\partial}{\partial R}\left(R v_{\text{mig}}(R)\Sigma_p\right) = \mathcal{F}(R)$$

Growth of the planets

Core: for planetesimals, we use the planetesimal accretion rates given by Inaba et al. (2001), while for pebbles we use the pebble accretion rates given by Lambrechts & Johansen (2014). So, the solid accretion rates in our model are given by

$$\frac{dM_c}{dt} = \begin{cases} \left.\frac{dM_c}{dt}\right|^{\text{Inaba}}_{\text{planetesimal}} = 2R_H^2\Sigma_p\Omega_P P_{\text{Coll}} & \text{if } S_t > 1 \\ \beta \left.\frac{dM_c}{dt}\right|^{\text{L\&J}}_{\text{pebble}} = \begin{cases} \beta 2 R_H^2 \Sigma_p \Omega_P & \text{if } 0.1 \le S_t \le 1 \\ \beta 2\left(\frac{S_t}{0.1}\right)^{2/3} R_H^2\Sigma_p\Omega_P & \text{if } S_t < 0.1 \end{cases} \end{cases}$$

With $\beta = \min(1, R_H/H_p)$ a factor that take into account that the scale height of small pebbles (H_p) could be greater than the Hill radius of the planet.

Envelope: the gas accretion rate and the thermodynamic state of the planet envelope are calculated solving the standard equations of transport and structure, using an adapted Henyey type code

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho_e} \quad ; \quad \frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4}$$

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{pla} - T\frac{\partial S}{\partial t} \quad ; \quad \frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla$$

Initial condition

We assume that the mass of the central star and the mass of the disk are:

$$M_\star = 1\,M_\odot \quad ; \quad M_d = 0.05\,M_\odot$$

The initial gas and solid surface densities are:

$$\Sigma_g = \Sigma_g^0\left(\frac{R}{R_c}\right)^{-\gamma} e^{-(R/Rc)^{2-\gamma}}$$

$$\Sigma_p = \eta\Sigma_p^0\left(\frac{R}{R_c}\right)^{-\gamma} e^{-(R/Rc)^{2-\gamma}}, \quad \eta = \begin{cases} 0.25 & \text{if } R < 2.7 \text{ au} \\ 1 & \text{if } R > 2.7 \text{ au} \end{cases}$$

with $R_c = 20$ au, and $\gamma = 0.9$ (Andrews et al. 2009, 2010). The disk is extended beetween 0.1 au and 1000 au using 5000 radial bins logarithmically equally spaced.

Results

We first calculated the evolution of the disk without any planet in it. We considered an unique size for the planetesimals/pebbles along the disk, and we did not consider the collisional evolution of them. So, the solid component of the disk evolves only by planetesimal/pebble migration.

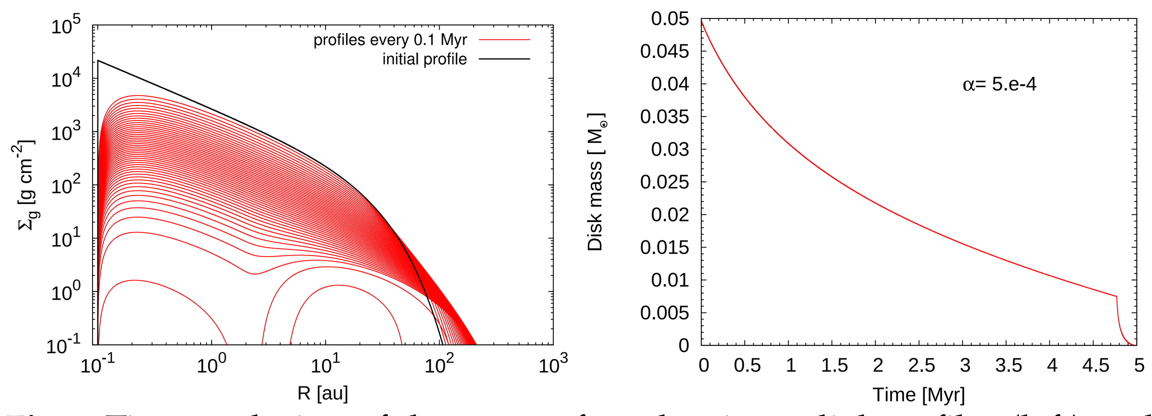

Fig 1. Time evolution of the gas surface density radial profiles (left) and the gas mass of the disk (right). We assume a value of $\alpha = 5\times10^{-4}$. The disk is dissipated in ~ 5 Myr.

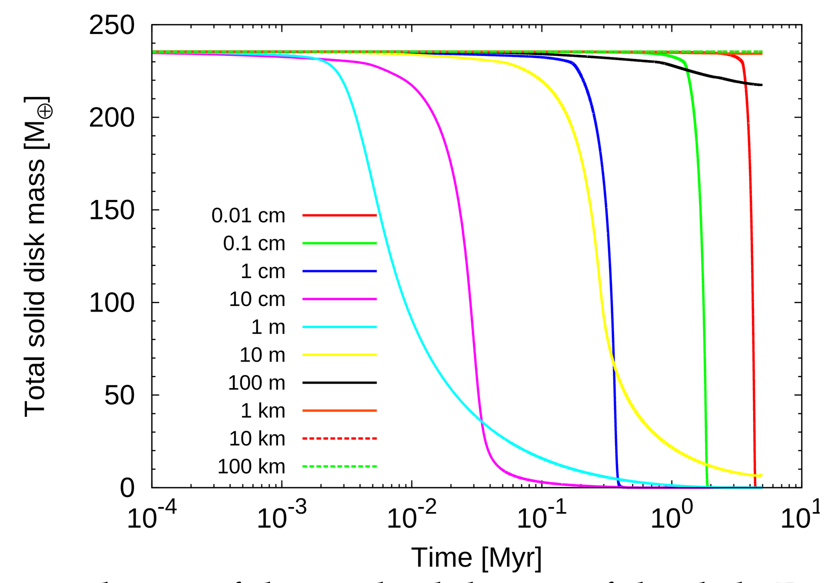

Fig 2. Time evolution of the total solid mass of the disk. For big planetesimal ($r_p \gtrsim 1$ km) migration could be negligible. However, for small planetesimals ($r_p \lesssim 100$ m) and pebbles ($r_p \lesssim 1$ m), migration plays an important role. For small particles, a significant amount of the total solid mass could be quickly loss. This imposes a strong time-constraint for the formation of massive cores.

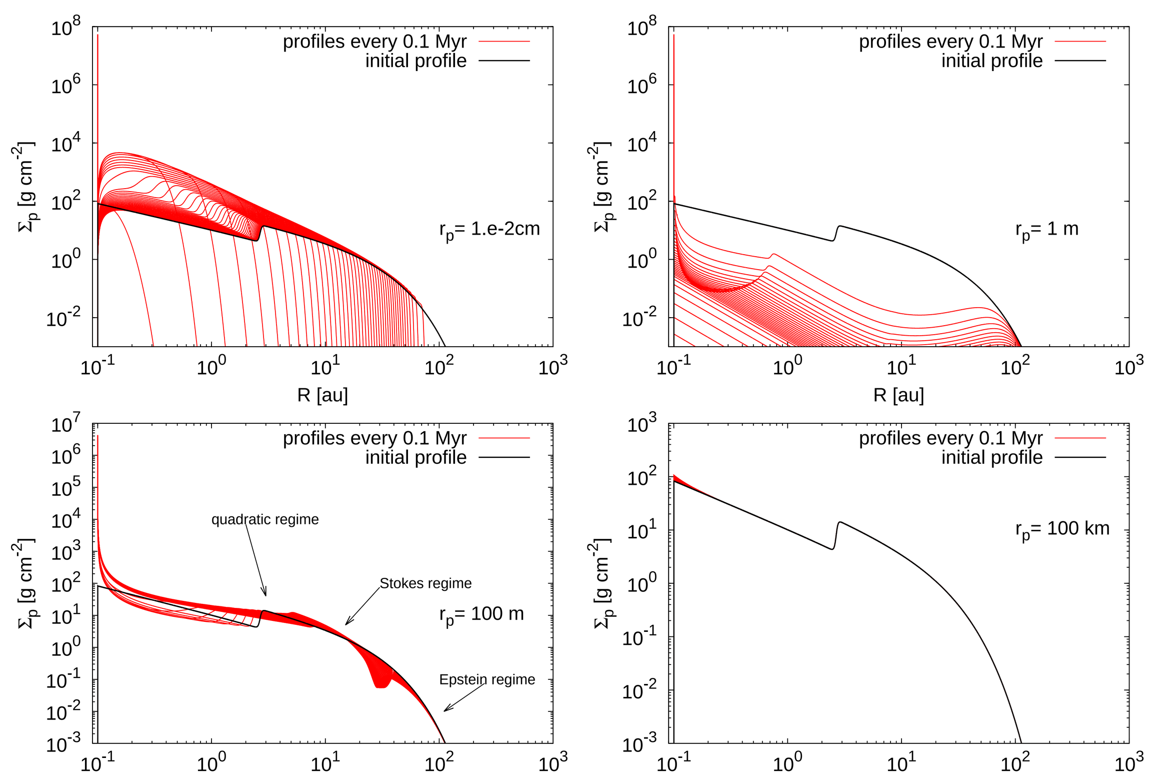

Fig 3. Time evolution of the solid surface density radial profiles for differents planetesimal and pebble sizes. Big planetesimals ($r_p \gtrsim 10$ km) are always in the quadratic regime along the disk. However, small planetesimals ($r_p \lesssim 1$ km), and pebbles, could be in different regimes along the disk (we show this in the case of $r_p = 100$ m). The evolution of the solid surface density radial profiles is very different for each planetesimal/pebble sizes.

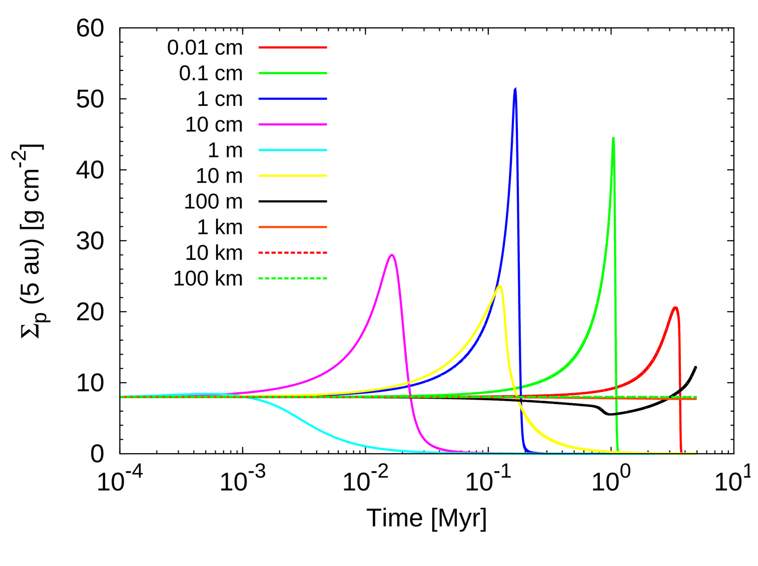

Fig 4. Time evolution of the solid surface density at 5 au. The inward migration of small particles, from the outer region of the disk, significantly increases the surface density. For big planetesimals, the surface density remains almost constant until the dissipation of the disk.

In situ giant planet formation at 5 au

We calculated the in situ formation of a planet at 5 au considering an homogeneous size planetesimal distribution. Simulations stopped when the planet achieved the critical mass (when the envelope mass equaled the core mass) or when the disk was dissipated (at ~ 5 Myr).

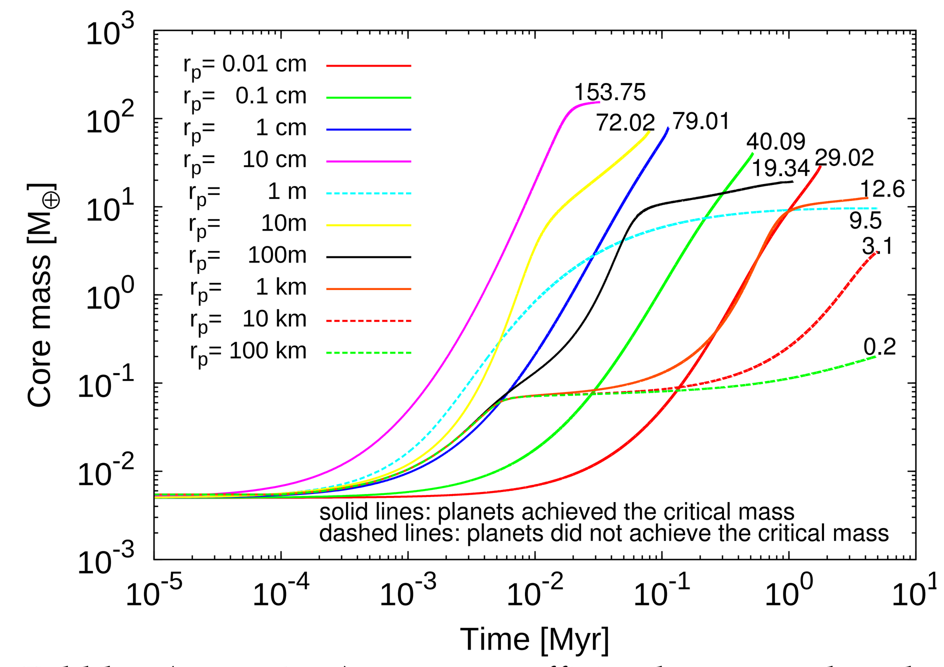

Fig 5. Pebbles ($r_p < 1$ m) are very efficiently accreted and massive cores are formed quickly. Planetesimals with 1 m $< r_p <$ 100 m are efficiently accreted too, due to the presence of the planet envelope which significantly increases the capture radius of the planet (Guilera et al. 2014).

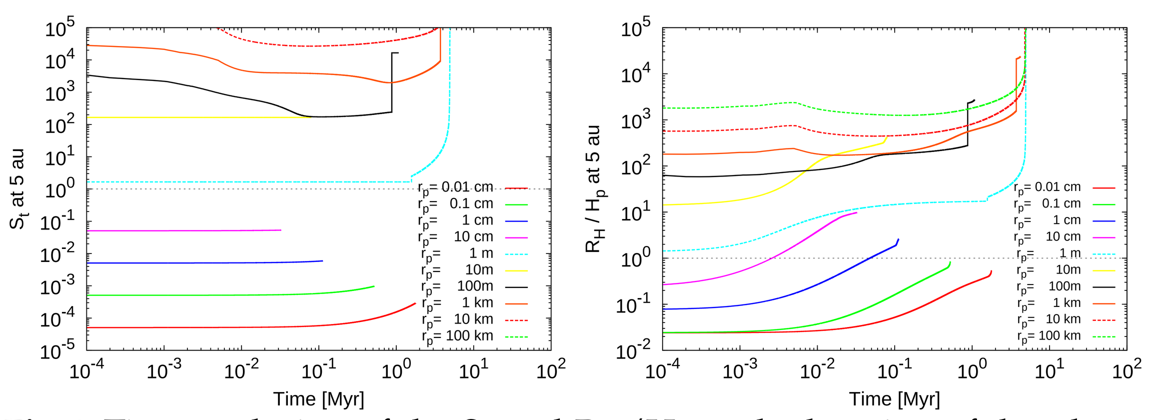

Fig 6. Time evolution of the S_t and R_H/H_p at the location of the planet. Particles with $r_p \lesssim 1$ m have always $S_t \lesssim 1$, so they are considered always as pebbles. For small pebbles, R_H/H_p remains always < 1, thus it is important to include the factor β in the pebble accretion rates.

Planetesimal size distribution and collisional evolution

We calculated again the in situ formation of a planet at 5 au, but now considering a planetesimal size distribution. We used 46 size bins between 0.01 cm and 100 km logarithmically equally spaced. Initially, all the solid mass is in the pebbles of 0.01 cm. The collisional evolution of the system is calculated using the model developed in Guilera et al. 2014 (considering coagulation/fragmentation between the particles along the disk).

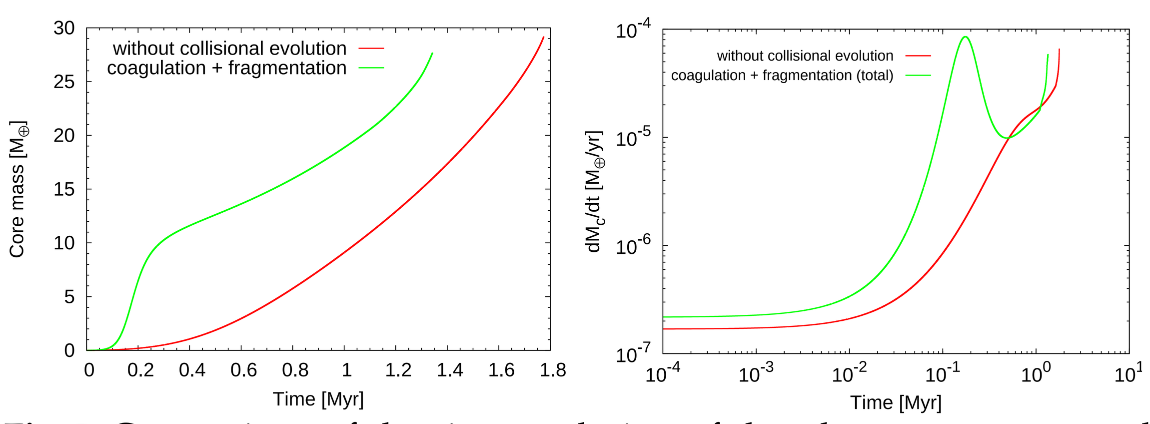

Fig 7. Comparison of the time evolution of the planet core mass and planetesimal-pebble accretion rate between the cases with, and without ($r_p = 0.01$ cm) solid collisional evolution. The coagulation between small pebbles significantly favors the quickly formation of a massive core.

Conclusions

Pebble accretion seems to be an interesting alternative in the formation of giant planets. The high accretion efficiency of these particles could solve the problem of the formation of massive cores before the dissipation of the protoplanetary disk. Global models of the solid evolution (coagulation/fragmentation + accretion + migration) are needed to study in detail the planet formation process. More accurate models are necessary: could these pebbles reach the core if the planet has a significant envelope ? High accretion rates are still valid for cores that could significantly perturb the surrounding gas ?

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