Giant planet formation via pebble accretion

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, Chiang, and Lambrichts & Johansen (2012) demonstrated that small particles, often called pebbles, with Stoke number $St < 1$ 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 $a^{1/2}/R_H$, with $a = R_H/R$, being $R$ 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, 2013, 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 Lambrecht & Johansen (2014) in order to study the formation of giant planets by pebble accretion. The main characteristics of our model are:

- solids 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 → a accretion disk + photo-vaporisation,
- 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 (+ photo-vaporization) for the gas surface density $\Sigma_g$.

$$\frac{\partial \Sigma_g}{\partial t} + \frac{3}{R} \frac{\partial}{\partial R} \left( \frac{\Theta}{2} \left( \Sigma_g \left( \frac{R}{R_e} \right) ^2 \right) \right) = \Sigma_e(R)$$

Solid component: a continuity equation for the solid surface density $\Sigma_p$.

$$\frac{\partial \Sigma_p}{\partial t} + \frac{\Theta}{2} \frac{\partial}{\partial R} \left( \Sigma_p \left( \frac{R}{R_e} \right) ^2 \right) = F(R)$$

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 Lambrecht & Johansen (2014). So, the solid accretion rates in our model are given by

$$\dot{M}_{\text{solid, planetesimal}} = \frac{2 \pi g \Sigma_p R^2 \rho_{\text{p,cell}}}{\gamma^2}$$

if $St > 1$

$$\dot{M}_{\text{solid, pebbles}} = \frac{1}{2} \frac{d R^2 \rho_{\text{p,cell}}}{\partial R}$$

if $0.1 < St < 1$

$$\dot{M}_{\text{solid, pebbles}} = \frac{1}{2} \frac{d R^2 \rho_{\text{p,cell}}}{\partial R}$$

if $St < 0.1$

With $\beta = \min(1, R_H/R)$ 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

$$\frac{\partial \rho}{\partial t} + \frac{1}{4 R^2} \frac{\partial}{\partial R} \left( R^2 \rho V_R \right) = 0$$

$$\frac{\partial \rho V_R}{\partial t} + \frac{1}{4 R^2} \frac{\partial}{\partial R} \left( R^2 \rho V_R^2 \right) = -\frac{1}{\gamma} \frac{\partial P}{\partial R}$$

$$\frac{\partial P}{\partial t} + \frac{1}{4 R^2} \frac{\partial}{\partial R} \left( R^2 \rho V_R ^2 P \right) = \frac{1}{\gamma} \frac{\partial (\rho V_R)}{\partial R}$$

$$\frac{\partial \rho}{\partial t} + \frac{1}{4 R^2} \frac{\partial}{\partial R} \left( R^2 \rho V_R \right) = 0$$

$$\frac{\partial \rho V_R}{\partial t} + \frac{1}{4 R^2} \frac{\partial}{\partial R} \left( R^2 \rho V_R^2 \right) = -\frac{1}{\gamma} \frac{\partial P}{\partial R}$$

$$\frac{\partial P}{\partial t} + \frac{1}{4 R^2} \frac{\partial}{\partial R} \left( R^2 \rho V_R ^2 P \right) = \frac{1}{\gamma} \frac{\partial (\rho V_R)}{\partial R}$$

Initial condition

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

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

The initial gas and solid surface densities are:

$$\Sigma_g = \Sigma_\odot \left( \frac{R}{R_e} \right)^{-\gamma}$$

$$\Sigma_p = \Sigma_\odot \left( \frac{R}{R_e} \right)^{-\gamma} \left( \frac{R}{R_p} \right)^{-1} \left( \frac{\rho_{\text{p,cell}}}{\rho_{\text{g,cell}}} \right)$$

with $\gamma = 0.25$ if $R < 2.7$ au

$$\gamma = 0.25$$

if $R > 2.7$ au

with $\Sigma_\odot = 100$ au and $\gamma = 0.9$ (Andrews et al. 2009, 2010). The disk is extended between 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.

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 pebbles of 0.1 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).

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