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On the diversity of giant planets—Simulating the evolution of solids in protoplanetary disks[☆]

K. Kornet[a,b,*], S. Wolf[a], M. Różyczka[b]

[a] *Max Planck Institute for Astronomy, Königstuhl 17, 69117Heidelberg, Germany*
[b] *Nicolaus Copernicus Astronomical Center, Bartycka 18,Warsaw 00-716, Poland*

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Abstract

We describe a model designed to track simultaneously the evolution of gas and solids in protoplanetary disks from an early stage, when all solids are in the dust form, to the stage when most solids are in the form of a planetesimal swarm. The model is computationally efficient and allows for a global, comprehensive approach to the evolution of solid particles due to gas–solid coupling, coagulation, sedimentation, and evaporation/condensation. We have used it to calculate the co-evolution of gas and solids starting from a comprehensive domain of initial conditions. Then based on the core accretion-gas capture scenario, we have estimated the planet-bearing capability of the environment defined by the final planetesimal swarm and the still evolving gaseous component of the disk. We describe how the disk's capability of formation of giant planets depends on the initial mass and size of a protoplanetary disk, its thermal structure, mass of the central star and properties of the material forming solid grains.

Keywords: Accretion disks; Protoplanetary disks; Planetary systems: formation; Extrasolar planets

1. Introduction

The architecture of a planetary system results from a chain of processes that start at the formation of a protoplanetary disk (PPD) around a nascent star. A PPD is a mixture of gas and solids and is made up from a material that, during the formation process, did not become directly part of the star, but, due to its excess angular momentum, remained in orbit around the newborn star. Global properties of PPDs, such as their masses and sizes are known in abundance from astronomical observations. Typical disk masses are between 0.001 and $0.1M_{\odot}$ and typical disk sizes are between few and a few hundred AU (see Beckwith and Sargent, 1993; Beckwith, 1994, and references therein). The ranges of about two orders of magnitude in observed masses and sizes of PPDs are partially due to different stages at which different disks are observed (Stepinski, 1998a) and partially due to an intrinsic scatter in initial conditions. On the other hand current radial velocity surveys led to discovery of over 170 extrasolar planets around main sequence stars (see Marcy et al., 2005; Mayor et al., 2004). The large majority of these planets are probable gas giant planets, as their masses are above $100M_{\oplus}$. A broad distribution of their orbital parameters suggests a large diversity in possible configuration of planetary systems. We postulate that indeed the dispersion in the initial conditions of PPDs leads to architecture diversity among planetary systems.

Three main theories have been proposed regarding the origin of planetary-mass objects. The first is dynamical fragmentation of a rotating collapsing protostar, the mechanism thought to be responsible for multiple stellar systems (reviewed by Bodenheimer et al., 2000a) and possibly the isolated planetary-mass objects observed in the young cluster σ Orionis (Zapatero Osorio et al., 2000). The second is gravitational instability in a disk (Kuiper, 1951;

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[*] Corresponding author. Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany.

E-mail address: kornet@camk.edu.pl (K. Kornet).

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Boss, 2000, 2002; Mayer et al., 2004; Durisen et al., 2005), in which, on a few dynamical time scales, a gravitationally bound subcondensation forms in a disk that at some location has a Toomre Q value on the order of unity. The third mechanism, known as the core accretion-gas capture process (CAGC), involves the relatively slow gradual accretion of small condensed particles in a disk, eventually resulting in a solid core of a few $M_\oplus$ which is able to gravitationally capture gas from the surrounding nebular disk (Perri and Cameron, 1974; Mizuno, 1980). Numerical calculations of Pollack et al. (1996) and Hubickyj et al. (2005) showed that the formation of a giant planet in this model can be divided into three phases. During the first one the solid core is formed by collisional accumulation of planetesimals. The second phase begins when the core reaches the mass of a few Earth masses and starts to accrete a significant amount of gas. During this phase the envelope stays in quasi-static and thermal equilibrium, as the energy radiated by the envelope is compensated by the energy released by accreted planetesimals. As during this phase the protoplanet accretes more gas than solids, the mass of the envelope finally becomes equal to the mass of the core. At this moment the third phase begins, during which the planet rapidly grows in mass by runaway accretion of gas. The final mass and location of the giant planet are determined by its gravitational interaction with its environment. As it grows in mass it induces spiral waves in the gaseous disk. It leads to the transfer of angular momentum resulting in the inward migration of the planet and possibly in the gap opening (Lin and Papaloizou, 1986; Lin et al., 1996; Ward, 1997). This last phenomenon strongly reduces the further growth of the planet.

The main problem with that scenario is related to the timescale required to form a giant planet in it. In general, it is of the same order of magnitude as the lifetime of the PPD, and it is not a priori certain if the giant planet is able to form before the disk disperses. Close to the star the formation time of a giant planets in the gas capture model is determined by phase 2, while at larger distances ($\gtrsim 10\,\mathrm{AU}$) the lengths of phases 1 and 2 become comparable. The durations of these two phases depend on the initial surface density of the planetesimal swarm at a given location. The larger the density, the faster the core grows and reaches higher mass at the end of phase 1. With the higher mass of the core, the length of phase 2 also diminishes. In general, at every distance from the star there is a critical value of the surface density of planetesimals which enables formation of a giant planet before dispersion of the PPD (for a more detailed discussion see Kornet et al., 2006). However, the density of the protoplanetary swarm is not in a simple relation with the density of gas in the disk from which it emerges. It is currently thought (for a review see Weidenschilling and Cuzzi, 1993; Beckwith et al., 2000) that planetesimals form via a buildup of progressively more massive particles by the process of coagulation. Therefore the surface density reflects the evolution of solid component of the PPD, which is governed by gas–solids coupling, coagulation, sedimentation, and evaporation/condensation. Due to these processes a significant redistribution of the solid material can take place, and in the inner part of the disk its surface density can be significantly enhanced compared to the initial value (Stepinski and Valageas, 1997; Weidenschilling, 2003). Consequently, the analysis of the diversity of giant planets resulting from the core accretion scenario should also include the global evolution of solids in PPDs.

In this paper we review the results obtained with the help of a simple approach to the formation of giant planet via CAGC scenario. Our model includes all important factors, at the same time remaining computationally cheap. It enables to investigate the population of giant planets from a large set of PPD with different parameters. In Section 2 we explain our approach to the evolution of PPDs and planet formation. The results of our calculations are presented in Section 3 and discussed in Section 4.

2. Methods of calculation

2.1. The disk

We model the PPD as a two component fluid, consisting of gas and solids—GPD and SPD, respectively. The gaseous component is described by the analytical model of Stepinski (1998b). In Stepinski's method the initial conditions are parameterized by the following three parameters: R_0, the initial outer radius of the GPD (in AU), M_0, the mass of the GPD at $t = 0$ (in units of $M_\odot$), and $M_\star$, the mass of the central star (in units of $M_\odot$). It is assumed that $M_\star$ stays constant during the evolution despite the fact that there is accretion from the disk onto the star. For the given values of these parameters, the analytical method yields an explicit, approximate formula $\Sigma(t, r; \alpha, R_0, m_0, M_\star)$ to the viscous diffusion equation composed of set of different power laws determined by different opacity behaviours in different temperature ranges. The resulting distribution of gas is close to the one coming from the numerical solutions of the equations governing the evolution of the GPD after the initial settle down phase. The viscosity coefficient is given by the standard α prescription:

$$\nu = \tfrac{1}{3}\alpha C_s H, \qquad (1)$$

where H is the density scale-height of gaseous disk and C_s denotes the speed of sound in the gas. All other quantities characterising the gas are obtained in a thin disk and vertical thermal balance approximation (see, for example, Frank et al., 1992), except the radial velocity of gas which is calculated from the continuity equation. The resulting gas accretion rate is nearly constant throughout the disk, with exception of the very outer parts of GPD where the gas moves outward.

In our model the SPD is a collection of solid particles of different sizes embedded in the GPD. The crucial approximation is that the size distribution of particles at