Diversity of Planetary Systems from Evolution of Solids in Protoplanetary Disks

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Abstract. We investigate dependence of planetary system size and mass on initial conditions of forming gaseous protoplanetary disk. The co-evolution of gas and solids is calculated for large set of initial conditions and evolution regimes. We find that great majority of initial conditions lead to either no planetary system or large planetary system. Solar-system-like configurations can be obtain from a rather restricted set of initial conditions.

1. Introduction

Solid protoplanets or planetary cores constitute the backbone of a our solar system onto which gaseous envelopes may be subsequently added. These protoplanets formed from planetesimals which themselves are thought to form via process of hierarchical coagulation starting from dust entrained in a gaseous protoplanetary disk (GPD). During the evolution of GPD solid matter experiences significant redistribution due to gas-solid coupling, coagulation, sedimentation, and evaporation/condensation. The collection of all solids in the GPD forms solids protoplanetary disk (SPD) that co-evolves together with, but not identically to, the GPD. Eventually, solids will coagulate into planetesimals and the evolution of the SPD will converge into a planetesimal swarm. We regard such a swarm as a surrogate planetary system, and further evolution of planetesimals into actual planets is not considered here. Thus following the evolution of GPD+SPD we can establish a link between initial conditions set by star and disk formation processes and the properties of the resultant planetary system. Considering a large set of viable initial conditions we can start addressing factors determining the large-scale character of potential planetary systems. In this paper we communicate our results regarding a dependence of bulk properties of planetary system (its size and mass) on initial conditions of GPD.

2. Our model

We assume that the GPD can be described as a viscous accretion disk. We use an analytic description of the evolution of such a disk given by Stepinski (1998). Assuming that the mass of central star is constant and equal to 1M☉ the initial conditions in Stepinski’s model are parameterized by only two quantities, the initial mass of the GPD, m0, and its angular momentum, j. The disk viscous driver is parameterized by uniform and constant viscosity parameter α. Our approach to the evolution of SPD is based on the method of Stepinski & Valageas (1996, 1997) who developed a simplified form of equations governing the evolution of the solids to processes described in Sect. 1. A numerical code originally described by Różyczka (1985), and based on the same philosophy as the popular ZEUS code (Stone & Norman 1992) was employed to compute the evolution of SPD.

We consider, in separate calculations, three distinct, idealized forms of solids (water ice, low-temperature silicates, and high-temperature silicates) to account for solids species with different condensation temperatures and bulk densities. The corresponding condensation temperatures are 150K, 400K and 1350K, and the corresponding bulk densities are 1, 2.6 and 3.3 g cm⁻³. The initial surface density of SPD is equal to the initial surface density of GPD multiplied by a factor of 0.01 for ice and 0.006 for silicates.

For every species of solids 484 evolutions of SPD were calculated, each run labeled by (j, m0, α). We use 11 values of j between 0.5 and 50 in units of 10⁵² g cm⁻² s⁻¹, 11 values of m0 between 0.02 and 0.2 M☉, and 4 values of α (10⁻⁴, 10⁻³, 10⁻² and 10⁻¹). Each SPD was evolved for 10⁷ years, long enough to form a planetesimal swarm, unless prior to that time the SPD was entirely accreted or evaporated. At the final time the radius Rₜ and the mass mₜ of the SPD were recorded.

3. Results

Fig. 1 shows the results of our calculations for water ice. Results for silicates are somewhat similar and will be published elsewhere due to the lack of space in this communication. The figure has four panels, each for a different value of α. For a particular value of α a 3D plot shows Rₜ(j, m₀) as a height of the surface and mₜ(j, m₀) as a color on the surface.

Overall, the dependence of an emerging planetary system on initial conditions can be summarized as follows. The domain of initial conditions (j, m₀) can be divided into two large portions, one which leads to no planetary
system and the other that leads to large and relatively massive planetary systems. The demarcation line between these two regimes, \( j = f(m_0) \) can best be characterized as a step function. The position of the demarcation line and the position of a step in this line depends on \( \alpha \), for smaller values of \( \alpha \) more and more initial conditions lead to existence of planetary system. For \( \alpha = 10^{-4} \) planetary system forms for all initial conditions.

Note that a transition zone in \((j, m_0)\) space between initial conditions leading to no planetary system and large planetary system is very narrow. That may suggest that most initial conditions lead to either no planetary systems, or large dust/planetesimal disks which may not develop planets but rather, due to their size, stay in the planetesimal phase, manifesting themselves as \( \beta \) Pictoris-type objects. Our results also suggest that initial conditions leading to a solar-system-like configuration are close to the transition zone.

**References**

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