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# THE GLOBAL PERSPECTIVE ON THE EVOLUTION OF SOLIDS IN A PROTOPLANETARY DISK

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**ABSTRACT.** It is currently thought that planets around solar-type stars form by the accumulation of solid matter entrained in a gaseous, turbulent protoplanetary disk. We have developed a model designed to simulate the part of this process that starts from small particles suspended in the gaseous disk at the end of the formation stage, and ends up with most of the solid material aggregated into 1-10-km planetesimals. The major novelty of our approach is its emphasis on the global, comprehensive treatment of the problem, as our model simultaneously keeps track of the evolution of gas and solid particles due to gas-solid coupling, coagulation, sedimentation, and evaporation/condensation. The result of our calculations is the radial distribution of solid material circumnavigating a star in the form of a planetesimal swarm. Such a distribution should well approximate the radial apportionment of condensed components of the planets spread over the radial extent of the mature planetary system. Therefore we view our calculations as an attempt to predict the large-scale architecture of planetary systems and to assess their potential diversity. In particular, we have found that some initial conditions lead to all solids being lost to the star, but we can also identify initial conditions leading to a radial distribution of solid material quite reminiscent of what is found in our solar system.

## 1. INTRODUCTION

Recently, with the identification of several solar-like stars showing evidence of planet-sized companions circling around them (Marcy and Butler, 1996a,b) , our interest in understanding the formation of planetary systems on their largest scale has intensified and widened beyond the long-standing question of the origin of the solar system. The increasingly well-characterized properties of the formation process of solar-like stars, as well as the character of the solar system, which is thought to be typical, give us growing confidence that planets around such stars form by the accumulation of solid matter entrained in gaseous disks surrounding those stars. It is therefore timely to develop a model, built from an evolutionary perspective and based on the global outlook, capable of predicting the overall architecture of planetary systems.

After the disk forms out of a collapsing molecular cloud fragment, the subsequent evolution of solids within it can be divided into several consecutive stages set apart by the physical processes dominating each of them. First, the disk goes through a dissipative stage evolving in such a manner as to feed material to the star while spreading out. It is during this stage that solid particles coagulate, settle toward the midplane, are advected toward the star, and can condense or evaporate in the changing gaseous environment. Thus, from the solids point of view, this stage is the age of major transformation. At the end of the dissipative stage surviving solids are deposited into planetesimals and the spatial distribution of solid matter around the star has little resemblance to that at the onset of this stage. During the next, accumulation stage, the backbone of the planetary system actually forms via the growth of planetesimals into solid protoplanets. The accumulation process apparently proceeds with only minimum radial displacement. Thus the distribution of solids on the scale of say 1 AU, as opposed to the scale of say $10^5$ km, is about the same before and after the final accumulation. Once planets form, they can migrate due to tidal interaction with a gaseous disk (Ward and Hourigan, 1989), interactions with unaccreted planetesimals (Fernandez and Ip, 1984), and the general instability of the solar system on the timescale of $10^9$ yr (Laskar, 1994). Yet, these migrations tend to be relatively small, and are not expected to rearrange the overall architecture of the planetary system. Thus, it seems that given a certain initial conditions at the end of the formation stage of the disk, the global evolution of solids during the dissipative stage plays a crucial role in determining the ultimate large-scale character of a planetary system.

On this basis we have developed a model that simultaneously keeps track of the evolution of the gas and the evolution of solid particles due to gas-solid coupling (Stepinski and Valageas, 1996a), as well as coagulation, sedimentation, and evaporation/condensation (Stepinski and Valageas, 1996b). This model takes the radial distribution of a dust surface density at the end of the disk formation as the input, and gives the radial distribution of the surface density of the solid material aggregated into planetesimals as the output.

## 2. COMPUTATIONAL MODELS

We applied our model to initial conditions sometimes considered fiducial by modelers of gaseous disks. The $1M_\odot$ star is surrounded by a viscously evolving disk characterized by dimensional viscosity $\alpha = 0.01$ with an initial gas surface density given by

$$\Sigma(r,t_o) = 8540\left[1+(r/15\mathrm{AU})^2\right]^{-3.78} \quad \mathrm{g\ cm^{-2}} \tag{1}$$

Thus, the initial distribution of the gas is practically constant, equal to about 8540 g $\mathrm{cm}^{-2}$, between the inner radius assumed to be at 0.036 A.U. and the radius of about 15 AU. At larger distances there is practically no gas. The total mass of the gaseous disk is equal to 0.245 $M_\odot$ and angular momentum is equal to $5.6 \times 10^{52}$ g $\mathrm{cm}^2$ $\mathrm{s}^{-1}$. Solid particles, assumed to be made up solely of water-ice, have initially all the same size, $s = 10^{-3}$ cm, and the surface density of the solid material constitutes 1% of the gas surface density to account for cosmic abundance. *The most important result of this, "high-mass model", calculation is that such a model leads to a complete loss of all solids into the star* (see Fig. 1).

We have also considered a scenario where the $1M_\odot$ star is surrounded by a viscously evolving disk characterized by $\alpha = 0.001$ with an initial surface density of the gas given by

$$\Sigma(r,t_o) = 2\left[1+(r/200\mathrm{AU})^2\right]^{-3.78} + 600(r/1\mathrm{AU})^{-1.5} \quad \mathrm{g\ cm^{-2}} \tag{2}$$

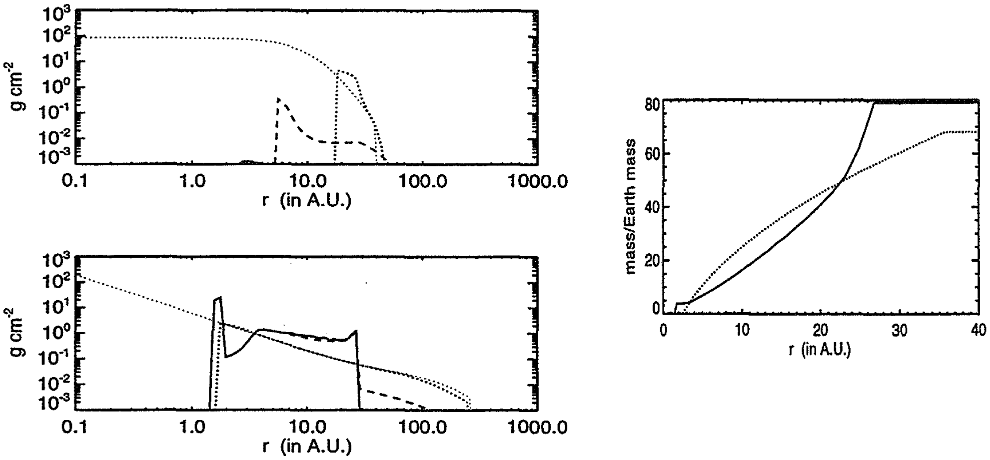

Figure 1. The two panels on the left side show the radial distribution of surface density of icy solids at selected times: $t = 10^4$ yr (dotted line), $t = 3.2 \times 10^5$ yr (dashed line), and $t = 3.2 \times 10^6$ yr (solid line). The light dotted line indicates the surface density of solids at the end of the formation stage. The upper panel shows the evolution of the high-mass disk, all solids are lost to the star. The lower panel shows the evolution of the low-mass disk, the surface density of solids converges when all solids are deposited into planetesimals. The sharp inner boundary of the distribution is located at the evaporation radius. The panel on the right side is a plot of the disk's mass interior to a given radius versus the radius. The dotted line represents the mass of icy planetesimals in the solar nebula "reproduced" by means of the minimum-mass concept (Hayashi et al. 1985) and the solid line depicts the mass of icy planetesimals predicted by our low-mass model.

The first term ensures that there is some mass up to very large distances from the star. The second term corresponds to the central concentration of the mass and sets the location of the evaporation radius. The total mass of the gaseous disk is equal to 0.023 $M_\odot$ and an angular momentum is equal to $1.8 \times 10^{52}$ g cm$^2$ s$^{-1}$. The solid constituent is prescribed as in the high-mass model. *The most important result of this, "low-mass model" calculation is that such a model leads to the survival of solid material* (see Fig. 1).

## 3. CONCLUSIONS

**Planetary systems diversity.** We have found that the shape of the distribution of gas and dust around the star at the end of the formation stage indeed makes a big difference in the ultimate location and the character of the planetesimal swarm. In particular, a disk evolving from the initial state characterized by a relatively large amount of gas concentrated relatively close to the star does not lead to the formation of planetesimals. On the other hand, solids in a disk evolving from the initial state characterized by a relatively small amount of gas extended over relatively large distances from the star develop into planetesimals.

**Character of planetary systems.** We have shown that the number density of planetesimals has an abrupt outer limit resulting from advectional compression. This leads to the prediction that planetary systems end abruptly. This is certainly true of our solar system, where the mass of all objects in the Kuiper belt is estimated to be only a fraction of Earth's mass (Jewitt & Luu 1995). It also appears that the final mass of solid material locked into planetesimals is about equal to the initial mass of solids at the end of the formation stage.

**Recovering the solar system architecture.** Among several models starting from the low-mass, extended initial mass distribution, the one characterized by dimensionless viscosity $\alpha = 10^{-3}$ yields the mass distribution in the planetesimal swarm that can lead to a planetary system like our own. Assume that four giant planets in the solar system have cores of $M_{\rm J} = 20M_{\oplus}$, $M_{\rm S} = 20M_{\oplus}$, $M_{\rm U} = 10M_{\oplus}$, and $M_{\rm N} = 10M_{\oplus}$ respectively. According to the minimum-mass concept the giant planets have locations $r_{\rm J} = 4.7$AU, $r_{\rm S} = 11.8$AU, $r_{\rm U} = 19.6$AU, and $r_{\rm N} = 26$AU. Applying this same mass apportionment formula for our model yields $r_{\rm J} = 4.05$AU, $r_{\rm S} = 15$AU, $r_{\rm U} = 21$AU, and $r_{\rm N} = 23.6$AU, which in these qualitative terms is not much different from the actual locations. The most important difference is the excess of mass near the outer limit of the mass distribution. This causes "Neptune" to be too close to "Uranus." The excess of mass at 20–30 AU may account for the mass lost from the plane of the ecliptic due to gravitational scattering of unaccreted planetesimals by planets that have already attained their final masses (Duncan et al. 1987).

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