From Dust to Planetesimals: Global Evolution of Ice in the Solar Nebula

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Abstract. Planets form by the accumulation of solid matter entrained in a gaseous solar nebula that accretes on the proto-Sun. We model part of this process starting from dust particles suspended in a gaseous disk, and ending up with most of the solid material aggregated into 1-10-km-sized planetesimals. At present, only water-ice solids are considered in our model. The model simultaneously keeps track of the viscous evolution of the gas and the evolution of solid particles due to gas-solid coupling, coagulation, sedimentation, and evaporation/condensation. We have found that the final radial distribution of (icy) solids is very sensitive to initial conditions. Fiducial initial conditions lead to all (icy) solids being lost to the proto-Sun. However, it is possible to find reasonable initial conditions that lead to a radial distribution of (icy) solid material similar to that found in our solar system.

1. Introduction

Over the last decade our attempts to understand the formation of the solar system on its largest scale focused on two concepts, accretion of the gas due to turbulent viscosity and coagulation of solid matter, which over time transform dust into large solid bodies - planetesimals. It is therefore timely to ask whether these concepts, when applied together, lead to the formation of a planetary system that looks anything like our own. To address this problem we have developed a model that calculates the simultaneous evolution of gaseous and solid components of the solar nebula starting from arbitrary initial conditions. The evolution of the gas is governed by viscous stress, parametrized by dimensionless viscosity $\alpha = 0.01$. The evolution of the solids is governed by the friction between the gas and the solids. Due to this friction, solid particles are partially coupled to turbulent eddies of the gas and, to a certain degree, mimic the behavior of the gas. In addition, there are differences between the mean velocities of solid particles and the gas, resulting in drag force acting on solid particles. All these effects strongly depend on particle size and are therefore modulated by the process of coagulation that continuously changes particle size distribution. The coagulation process, the rate of which depends on the density of the solid particles, is itself modulated by the settling of solids toward the equatorial plane. Moreover, as particles spiral toward the proto-Sun, they move into an ambient gas hot enough to evaporate them. The conditions of the ambient gas continuously change as the accretion process diminishes the mass of the disk, thus changing all its physical properties.

2. Results

First, we applied our model to initial conditions considered fiducial [2] by modelers of gaseous disks. Thus, our computation starts at $t = 0$ with a disk of $0.245 M_\odot$ and an angular momentum of $5.6 \times 10^{22}$ g cm$^2$ s$^{-1}$. The initial surface density of the gas, $\Sigma$, is practically constant between the inner radius at 0.037 A.U. and the outer radius at 15 A.U. The solids, in the form of 1-mm particles, are uniformly distributed throughout the gas, and their surface density, $\Sigma_s$, equals $10^{-2} \Sigma$. This is a relatively hot disk, and the ice/vapor interface is located beyond 10 A.U. for the first $10^5$ yr. However, on a timescale of about $10^4$ yr, particles located beyond this interface coagulate to sizes of the order of 1-10 cm and quickly move inward where they evaporate. As their inward movement is swift, they have no time to grow and stop their motion toward destruction. The end result is that particles never grow to sizes bigger than about 10 cm, and eventually all are destroyed, leaving a purely gaseous disk behind. It is clear that, according to our model, initially massive and relatively compact solar nebula will produce no icy (or any other) planetesimals.

In order to produce icy planetesimals in the region corresponding to the outer solar system we have to start with a much less massive and more extended disk. We consider the following initial conditions: disk mass = 0.0238 $M_\odot$, angular momentum = $1.8 \times 10^{22}$ g cm$^2$ s$^{-1}$, and $\Sigma(t = 0)$ as given by the upper left panel on Fig. 1. These initial conditions ensure that there is some mass up to very large distances from...
the proto-Sun, so we can eventually lock some solids at distances up to \( \sim 30 \) A.U. They also ensure that there is enough mass around the evaporation radius to form an initial particle barrier (see below). Figure 1 shows the evolution of the surface density of the gas and the solids starting from the initial conditions described above. At \( t = \) 0 yr the evaporation radius is located just outside \( 3 \) A.U. and the particles are all small and coupled to the gas. At \( t = 2 \times 10^4 \) yr the evaporation radius moves to about \( 2 \) A.U. and particles just outside this radius reach \( 100 \) cm, whereas particles located farther away are smaller. At \( t = 10^6 \) yr particles just outside the evaporation radius have planetesimal-like sizes of about \( 10^5 \) cm and are decoupled from the gas; they will practically remain in this location and are available for further growth into planets or planetary cores. From \( t = 10^6 \) yr on the evolution of the gas slows down (as viscous torque is proportional to the gas surface density) and the evaporation radius changes very slowly. At time \( t = 10^6 \) yr the distribution of icy solids converges to its final form. All solids are concentrated into \( 10^8-10^9 \)-cm planetesimals and their total mass is about \( 63M_\text{Sun} \). They populate the region between about \( 1 \) A.U. and \( 30 \) A.U. with increased concentration inward.

### 3. Conclusions

According to our model, coagulation of solid particles in an accreting solar nebula may, but does not necessarily, lead to the formation of planetesimals. Whether planetesimals form, and where, depends strongly on the initial conditions. As particles grow by coagulation they reach a size of \( 1-100 \) cm when their radial velocities are at the maximum. As they move toward the proto-Sun, they either "outgrow" their problem by increasing their size, slowing down and eventually decoupling from the gas, or they fall into the evaporation zone and are eventually accreted by the proto-Sun in the form of vapor.

As coagulation is more effective at smaller radii, large particles appear first outside the evaporation radius. Providing they manage to stop moving inward before evaporating, they will form a motionless barrier that captures all other particles falling from the outer portion of the disk. In order for such a barrier to form, a disk must have a certain size; too small a disk will form no barrier as all particles will evaporate. Once the barrier is established, all solids located outside it will either fall on it and accumulate at the barrier's radial location or grow large before reaching it and accumulate at larger radii. Thus, the total mass of all planetesimals is "frozen" once the barrier forms near the evaporation radius.

To produce the solar-system-like distribution of icy solids the evaporation radius should be located at about \( 5 \) A.U. for as long as is needed for particles to coagulate into \( \sim 10^4 \)-cm particles. As this happens the total mass of solids located beyond \( 5 \) A.U. should be equal to the total mass of solids currently found in giant planets. Furthermore, they should be distributed over long radial distances so not all of them will fall onto the barrier and form one giant planet, but instead a radial distribution of material reaching as far as \( 30 \) A.U. can be established. Starting from the initial conditions presented above many features of the outer solar system solid mass distribution can be obtained. Notice, however, that the particle barrier forms between \( 1 \) A.U. and \( 2 \) A.U. and not around \( 5 \) A.U. This should not be viewed as a disappointment, as our initial conditions are arbitrary and ones resulting in a better fit can be found. The important conclusion from this calculation is that the architecture and the very existence of a planetary system seem to be very sensitive to initial conditions. In this context our solar system may be quite unique and not easily reproducible.

### References
