

Planetesimals Capture and Grains sedimentation in the Disk Instability Model

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We present an evolutionary model of a protoplanet created by the disk instability mechanism (Boss 2002). We show that such a body contracts slowly for the first $\sim 4 \times 10^5$ years, after which there is a rapid collapse to planetary dimensions. We find that during the slow contraction phase, the protoplanet can accrete a significant fraction of solid material in its feeding zone, thus enriching it with heavy elements. In addition, we find that silicate grains larger than about 1 cm can sediment to the center and form a core.

We begin with a quasi-static model of a Jupiter-mass object with a radius of ~ 0.5 AU, similar to the initial "clump" in the model of Boss (2002). We follow the evolution using an adaptive mass zoning code. Fig. 1 shows the evolution of the protoplanet's central temperature, effective temperature, central pressure and radius as a function of time up until the rapid collapse stage.

Planetesimal Capture:

The evolution was computed assuming that the composition of the protoplanet is solar. At each stage in the evolution we followed the trajectories of planetesimals as they passed through the protoplanetary envelope using the planetesimal ablation code of Podolak et al (1988) to compute the critical impact parameters and the effective radii depend on the protoplanetary density distribution, as well as on the size, composition and random velocity of the planetesimals. The random velocity of the planetesimal far from the protoplanet was taken to be to be 1 km/s.

We computed the accreted mass for three different sizes of planetesimals: 1, 10 and 100 km. The composition of the planetesimals was assumed to be a mixture of ice, rock and CHON. Fig.3 shows how the critical impact parameters and the effective radii depend on the protoplanetary density distribution, as well as on the size, composition and random velocity of the planetesimals. The random velocity of the planetesimal far from the protoplanet was taken to be to be 1 km/s.

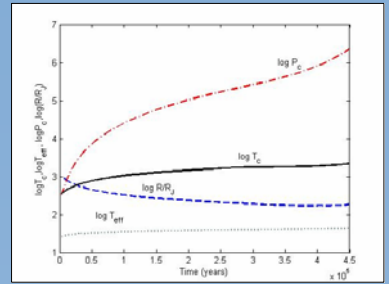


Fig. 1 Variation of protoplanet central temperature, effective temperature, central pressure and radius with time.

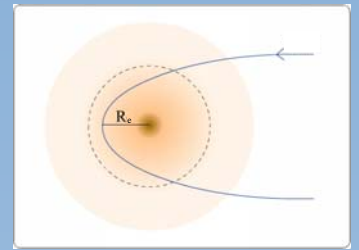


Fig. 2 Trajectory of planetesimal through the protoplanetary atmosphere

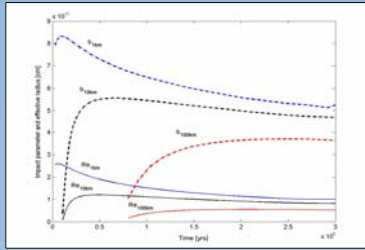


Fig. 3 The critical impact parameter and the effective radius for the three different sizes of planetesimals (made of ice+rock)

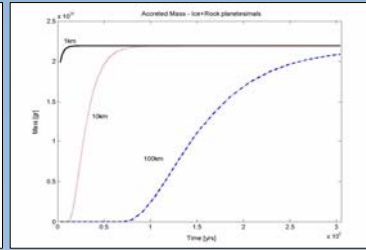


Fig. 4 Accreted mass as a function of time for the 3 different sizes.

Fig. 4 shows the accreted mass as a function of time for the 3 different sizes. 1km planetesimals can be captured almost immediately, while 10km planetesimals can only be captured after the protoplanet has contracted for some tens of thousands of years. 100 km planetesimals require $\sim 10^5$ yr of evolution before the average density of the protoplanet becomes high enough to capture them. In the first two cases all of the available planetesimal mass is captured. In the case of 100 km planetesimals $\sim 90\%$ of the available mass is captured.

Grain Sedimentation:

The sedimentation was computed assuming the grains are solid and spherical. We allowed for coagulation of grains at each level in the atmosphere. Fig. 5 shows the mass per shell in the evolving protoplanet as a function of time for grains that are initially 1, 0.1 and 0.01 cm in radius.

As can be seen, the 1 cm grains sediment to form a core in just over 103 years. For 0.1 cm grains the time required is closer to 3×10^4 years. For 0.01 cm grains, the sedimentation time is of the order of 10^5 yrs. During this time the protoplanet contracts substantially, and internal temperatures become high enough to vaporize the grains so that not all the sedimented mass reaches the core.

When convection is included, the grains are carried by the convective flux. If we assume that grains that reach the center can be carried back up by the convection, only grains of 1 cm or larger will remain in the center to form a core. Smaller grains are coupled to the gas and eventually evaporate when the envelope temperatures are high enough.

If we assume that the grains that reach the center are incorporated into a core and do not participate in further transport, then even grain as small as 0.01 cm can sediment to form a core.

We computed the grain sedimentation rates for other types of grains as well. Icy grains evaporate in the atmosphere before reaching the core for all sizes of grains. CHON grains lead to similar results, but if the CHON grains are big enough (10cm, 1m) they sediment down before the inner layers reach high temperatures and help to form a core.

References:

Boss, A. (2002). *Astrphys. J.* 576:462

Podolak, M., Pollack, J. B., and Reynolds, R. T. (1988) *Icarus* 73:163.

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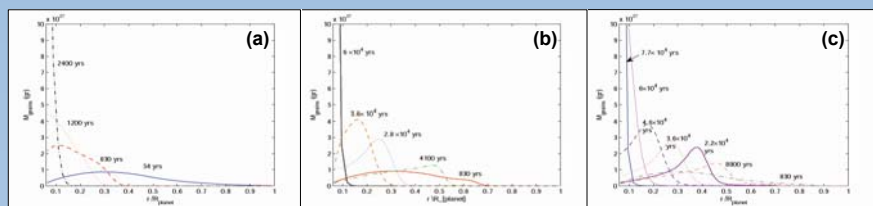


Fig 5. Grain mass per shell as a function of time(sec) for 1 (a) 0.1 (b) and 0.01 (c) cm silicate grains, for a non-convective atmosphere

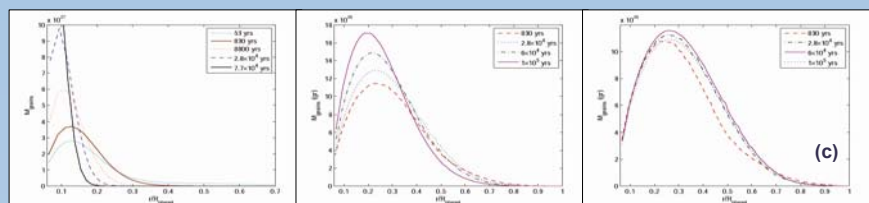


Fig 6. Grain mass per shell as a function of time(sec) for 1 (a) 0.1 (b) and 0.01 (c) cm silicate grains, for a convective atmosphere