EPSC Abstracts
Vol. 6, EPSC-DPS2011-934, 2011
EPSC-DPS Joint Meeting 2011

Core formation in accreting planetesimals

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Abstract

We have studied the influence of melting, melt migration and the associated redistribution of radioactive heat sources on the thermo-chemical evolution of planetesimals. Our work provides constraints on the timing and duration of the core formation and the internal structure for planetesimals that did not experience partial melting larger than ~50%, i.e., an internal magma ocean is absent.

1. Introduction

The compositions of meteorites and the morphologies of asteroid surfaces provide strong evidence that partial melting and differentiation were widespread among the planetesimals of the early solar system. Planets may have been formed from differentiated planetesimals and differentiation of the proto-planets may have been facilitated by planetesimals being pre-differentiated. However, it is not easily understood how planetesimals can be differentiated. To account for significantly smaller radii, masses, gravity and accretion energies early, intense heat sources are required. The short-lived nuclides ^{26}Al and ^{60}Fe have been proposed as a plausible heat source due to their widespread presence in the early solar system significantly higher specific powers but much shorter half-life times than those of long-lived nuclides. Here, we investigate the process of differentiation and core formation in accreting planetesimals taking into account the effects of sintering, melt heat transport via porous flow and redistribution of the radiogenic heat sources.

2. Computational Model

Our mathematical model is based on the model by [1], which considers the accretion of planetesimals by radial growth. We use a spherical, one-dimensional model of a partially molten planetesimal. The common heat conduction equation for a case that heat is transferred by conduction only has been modified to consider also melt segregation. In the initial state, the planetesimals are assumed to be highly porous as they formed as aggregates of fine dust and unconsolidated grains of a mixture of Fe-FeS and silicates. The thermal conductivity of the material depends strongly on the porosity of the material and we use the same approximation as [2]. The porosity of a planetesimal changes due to so called hot pressing, i.e., sintering. To simulate this change, we follow the approach of [3]. Melt segregating from the solid mantle transports the energy of the hot material. This transport becomes more significant with increasing melt fraction. The heat transport via magma segregation is treated according to the flow in porous media theory. The segregation of melt is simulated using the Darcy flow equation, which depends on the permeability of the material. At the beginning of a simulation the heat producing nuclei are distributed homogeneously, later this may change due to melting and subsequent chemical differentiation, as the heat source distribution depends on volume fractions of Fe-FeS and silicates. ^{60}Fe is enriched in the iron melt and ^{26}Al in the silicate melt.

3. Results

We consider a small body that accreted either instantaneously or linearly from the initial radius of 1 km to the final radius of 17 km within 1 Ma, starting contemporary with the CAIs. We further assume that molten iron can permeate through solid silicate even with a low degree of melting and without silicate melting [4]. The onset time and the end of core formation (time when the core radius remains constant) are shown in Fig. 1 as functions of the grain size. Depending on the grain size b (relevant for the Darcy flow equation) a pure iron core ($b \geq 0.1$ mm), an iron-dominated core including silicates ($0.05 \leq b < 0.1$ mm) or no core at all ($b \leq 0.05$ mm) forms. In general, Fe-FeS separation starts later in the accreting cases in contrast to the instantaneous ones. Furthermore, the core formation process takes longer

for time-dependent accretion except for small values of b, where the high peak temperatures in instantaneously formed planetesimals prolong core formation substantially with times up to 3 Ma. The final core size (if any core has formed) is always smaller for the accreting bodies due to lower peak temperatures and hence smaller amount of partial melting. Interestingly, for larger planetesimals the duration of core formation is similar as long as the melt content does not increase to more than ~50%.
Our finding is in contrast to the results by [5], who

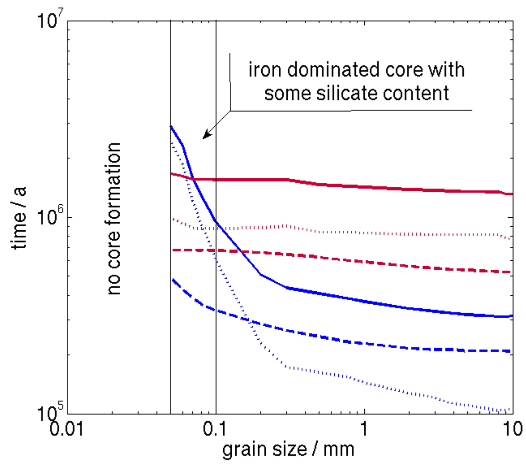

Fig. 1. Time vs. grain size. The onset time (dashed lines), end time (solid lines) and duration (dotted lines) of the core formation for an exemplary body with a final radius of 17 km accreting either instantaneously (blue lines) or linearly within 1 Ma (red lines) starting contemporary with the formation of the CAIs.

simulated the gradual growth of the iron core due to inward flow of Fe-FeS melt towards the center of the planetesimal by assuming a fixed migration rate of 300 m/yr. They conclude from their models that core formation is close to instantaneous for small planetesimals (smaller than 50 km) when accretion was completed before 2 Ma and for a fast accretion time (smaller than 0.01Ma). This assumption is only compatible with our results for grain sizes of about 10 mm. Grain sizes of primitive chondrites, however, are estimated to be 0.1 mm or less [7], resulting in a slow iron core formation (> 1Ma) possibly with a fraction of silicates enclosed. In additional calculations, we have varied the liquidus temperature of iron and assumed that iron starts to migrate only when silicate begins to melt. For these cases the process of core formation takes even longer. Thus, we suggest that the core formation of planetesimals, for which the melt content does not increase above 50 %, is not instantaneous but a slow process that can take up to several Ma depending on the onset and duration of the accretion process – if it takes place at all. This has also implications on their thermal evolution and temperature distribution in planetsimals. Note, however, we assume that the grain sizes do not to change with time, which seems to be valid only if iron but not silicate melts [6]. For silicate melting, the matrix would not remain so fine grained once melting starts [7] and an increase of the grain size via Oswald ripening might enhance melt segregation. In general, this would favour core formation but the associated heat transport also cools the interior and decreases the amount of melting, leading again to slower core formation.
In all considered cases the separation between silicate and iron was not complete and also the silicate melt that rose due to the Darcy flow solidified in the cooler upper layers before it could reach the surface. The outer layer remained undifferentiated but the deeper part of this layer lost its porosity due to sintering. Thus, the typical structure consists of a Fe-rich core, a silicate mantle, an undifferentiated (primordial) but sintered layer and an undifferentiated and porous surface layer.

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