DIFFERENTIATION OF H-CHONDRITIC PLANETESIMALS. W. Neumann[1] and D. Breuer[1] and T. Spohn[1], [1]Deutsches Zentrum für Luft- und Raumfahrt, Institut für Planetenforschung, Rutherfordstraße 2, 12489 Berlin, Wladimir.Neumann@dlr.de, Doris.Breuer@dlr.de, Tilman.Spohn@dlr.de.

Introduction: The compositions of meteorites and the surfaces of asteroids indicate that partial melting and differentiation were ubiquitous in the planetesimals of the early solar system. Planetary formation could have been facilitated by the planetesimals being pre-differentiated[1]. However, it is not well understood how planetesimals can be differentiated. As one must account for lower gravity and smaller radii, the differentiation of planetesimals requires early, intense heat sources producing considerably more power than the decay of U, Th and K, like ^{26}Al and ^{60}Fe. With respect to the degree of differentiation meteorites form two classes: chondrites originating from undifferentiated parent bodies and achondrites, iron meteorites and stony and stony-iron meteorites originating from bodies apparently fraction3ated into a mantle and a core. A large variety in the degree of differentiation has been identified: metal separated partially or completely from silicates and silicates fractionated from each other, causing the composition of rock to deviate moderately to strongly from a primitive chondritic composition[2][3]. Differentiation of planetesimals must have occurred within the first few million years of the solar system judging from the ages of meteorites and the surfaces of asteroids. Further evidence for rapid iron-silicate differentiation comes from ^{182}Hf-^{182}W concentration variations in iron meteorites[4][5] and for basalt formation from the concentrations of ^{26}Al-^{26}Mg and ^{53}Mn-^{53}Cr in eucrites and angrites[6][7].

Here, we investigate the process of differentiation in ordinary H-chondritic planetesimals taking into account the effects of accretion, porosity, sintering, melt heat transport via porous flow and redistribution of the radiogenic heat sources. We also study the influence of those effects on the thermo-chemical evolution of planetesimals. Our work provides constraints on the amount of heating, the timing and duration of the differentiation and the internal structure for planetesimals that did not experience partial melting larger than ~50%, i.e., an internal magma ocean is absent.

Computational Model: We use a spherical 1D-model of a partially molten planetesimal. The implementation of accretion as radial growth is based on the model by [8]. We have modified the heat transport equation for a case where heat is transferred by conduction only to consider also heat loss due to the migration of iron and silicate melts. In the initial state, the planetesimals are assumed to be highly porous as they accreted as aggregates of fine dust of a mixture of Fe-FeS and silicates. The thermal conductivity is a function of porosity and composition. For porous material we use the fit[9] $k = k_b\left(\exp(-4\phi/\phi_1) + \exp(-4.4 - 4\phi/\phi_2)\right)^{1/4}$, where $\phi_1 = 0.08$, $\phi_2 = 0.17$ and k_b is the mean conductivity of the compact material and is calculated using the geometric mean model with pure mineral thermal conductivities from [10]. The porosity ϕ of a body changes due to so called hot pressing, i.e., sintering. To simulate this, we follow the approach of [11] by solving the equation $\partial(1-\phi)/\partial t = A\sigma^{2/3}b^{-3}\exp(E/RT)$, with the activation energy E, the gas constant R, the temperature T, the grain size b, the effective stress σ and the number A lying between $1.5\cdot10^{-5}$ and $5.4\cdot10^{-5}$.

Melt segregating from the solid matrix (i.e., sinking iron and ascending silicates) transports the energy of the material. This transport becomes more significant with increasing melt fraction (whereby the latter depends among other parameters on the assumed liquidus temperatures of the phases, e.g., iron liquidus of 1233 K for sulfur-rich material and 1700 K for low sulfur fractions). The heat loss due to magma segregation is treated according to the flow in porous media theory by supplementing the heat conduction equation with additional advection terms. To simulate the segregation of melt, the relative velocity between the melt and the matrix is computed using the Darcy flow equation, which depends on the permeability of the material. In the present model, we neglect that melt might be also able to rise toward the surface via dykes. In that case a basaltic layer could from at the surface as it is asuggested for Vesta. In the initial stage of the planetsimals 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 the fractions of iron and silicates. ^{60}Fe is enriched in the iron melt and is trans-

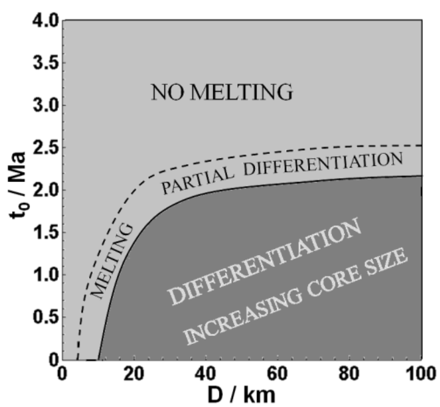

Fig. 1 Constraints on the formation time (assuming instantaneous accretion) and on the terminal radius (cf. caption of Fig. 2) for a planetesimal to differentiate.

ported towards the center, whereas ^{26}Al moves to the upper layers of the body together with the silicate melt.

Results: The results show that even in a small planetesimal with the radius of only a few km the heat production by the short-lived radioactive nuclei suffices to achieve melting assuming an initially porous state. Initially porous bodies reach considerably higher peak temperature compared to initially compact bodies of equal size.

Figure 1 illustrates for which conditions, i.e., the formation time assuming instantaneous accretion and the radius of a planetsimal, the planetsimal starts to melt (partial differentiation) or is differentiated into an iron core. Small or late accreted bodies even remain below the threshold temperature for sintering, do not sinter and keep their porous nature. Bodies that reach the threshold temperature for sintering in certain areas but do not melt (or melt but do not differentiate due to unfavorable geometry, low sulfur content or too low temperatures), lose porosity in the regions around the centre with a certain radius. They consist of a sintered interior and a porous outer shell. If the melting temperature of iron is exceeded the degree of differentiation can vary considerably. A typical structure of a differentiated planetesimal consists of an iron core, a silicate mantle, an undifferentiated but consolidated layer and a porous primodial layer. Under favorable conditions (i.e., high sulfur fraction, early accretion and initially porous state) even bodies as small as ~ 8 km in radius could have differentiated.

It is important to note that peak temperatures are dampened by any kind of non-instantaneous accretion (Fig. 2). We have tested linear, exponential and asymptotical laws and they yield increasingly lower temperatures compared to the instantaneous formation. Prolonged accretion duration has a similar effect. Hence the extent of melting varies not only with the onset time but also with the duration of accretion as well as with the accretion law. A similar relation exists between the accretion and the extent of sintering. The thickness of the porous regolith layer increases from the instantaneous formation to linear, exponential and late runaway accretion.

On the contrary to current assumptions [12,13], we find that the differentiation and hence the formation of cores in planetesimals is not an instantaneous process. The duration of core formation depends strongly on the sulfur content. High content of FeS results in fast differentiation (≤1 Ma) , low sulfur fraction may result in slow differentiation (up to 10 Ma) or no differentiation at all.

Interesting to note is also that for a S-rich material (with a low liquidus temperature of the iron) the core forms rather prior to silicate melting at temperatures below ~1425 K. For a low S fraction (iron liquidus at about 1700 K) the interval between the solidus and the liquidus of iron is almost 500 K. Iron melting is hence considerably less prominent below the silicate solidus and the differentiation starts during the melting of silicates.

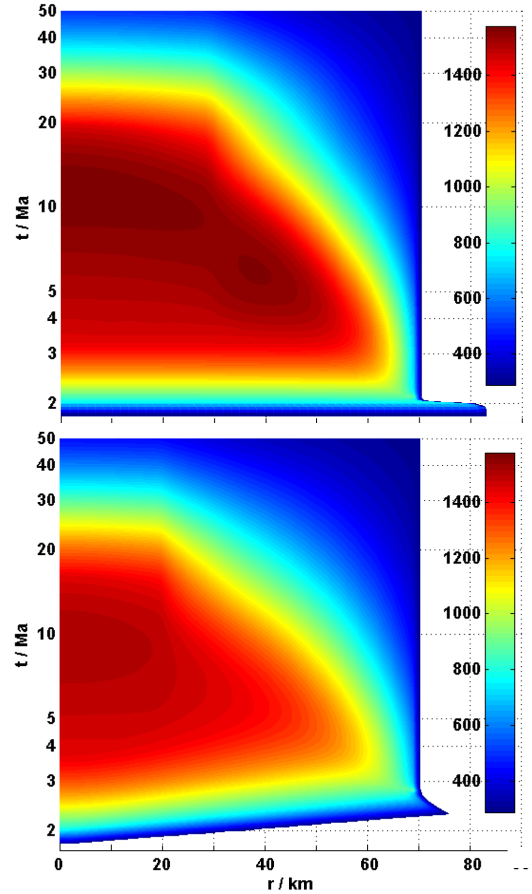

Fig. 2 Temporal evolution of the radial distribution of the temperature. Upper panel: A body that accretes instantaneously at 1.8 Ma to the terminal radius of 70 km. Lower panel: A body that accretes linearly within 0.5 Ma starting at 1.8 Ma with the initial radius of ~1.2 km and a terminal radius of 70 km. The terminal radius is the theoretical radius of a body with the same composition, but without pores. In the lower panel accretion shifts the differentiation to the time when the heat generation is dominated by ^{60}Fe. Hence, by contrast to the upper panel, no change in the temperature structure occurs.

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