MODELING THE EARLY THERMAL EVOLUTION OF METEORITE PARENT BODIES BASED ON NEW THERMAL CONDUCTIVITY MEASUREMENTS OF HIGHLY POROUS AGGREGATES.

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Introduction: In recent years, studies using high resolution radioisotope chronology yielded significant advance in understanding formation and evolutionary time scales of meteorite parent bodies. One line of evidence demonstrated that the internal heat source for early differentiation and metamorphism was decay heat of short-lived nuclides like ^{26}Al or ^{60}Fe [1-4]. This can be reconciled with studies demonstrating that differentiated meteorite parent bodies are among the oldest objects, and formed more or less contemporaneously with CAI [3,5,6], while chondrite parent bodies formed later – postdating individual chondrule formation, which in most cases occurred 1-4 Ma after CAI [7-9]. Formation and cooling ages or cooling rates obtained by radioisotope chronology can be quantified by models of asteroidal thermal evolution that simulate physical and chemical processes in more or less detail [4,10,11].

As planetesimals initially grow from dust in protoplanetary discs, they start as highly porous and fragile bodies [12]. As in high porosity bodies the dust particles have only few contacts between neighboring monomers of the material and/or very small contact areas between them, a significantly lower thermal conductivity is expected than in more compact bodies, which results in stronger heating before sintering and solidification occurs. We experimentally determined the heat conductivity of porous aggregates and modelled the effects on the early thermal history of meteorite parent bodies.

Methods: The determination of the thermal conductivity was performed by a combination of laboratory experiments and numerical simulations [13]. An IR camera measured the temperature distribution of the sample surface heated by a well-characterized laser beam directed onto porous dust samples, consisting of spherical, micron-sized SiO_2 particles. With volume filling factors in the range of 15% to 54%, the thermal conductivity was 0.002 to 0.021 Wm^{-1} K^{-1} (Fig. 1).

We calculated the structure and thermal evolution of porous planetesimals for different initial radii R and instants of formation t_{form}. The bodies are assumed to have a spherically symmetric structure. The density of matter is given by $\rho=\rho_b(1-\phi)$, where ρ_b is the (constant = 3700 kg/m^{-3}) bulk density of planetesimal material, and ϕ is the volume fraction filled by the pores.

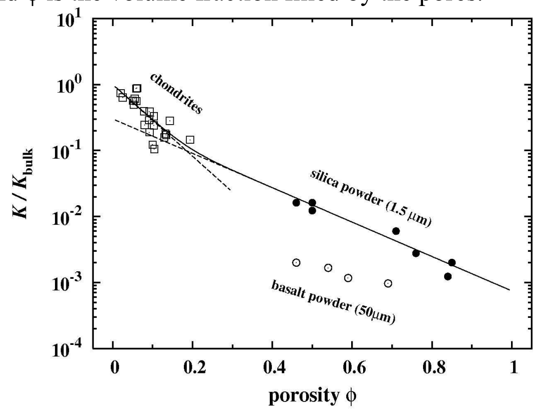

Figure 1. Variation of heat conductivity K with porosity ϕ. Results for silica powder (filled circles) from our experiments [13], and for particulate basalt (open circles) from [14]. Open squares are experimental results for ordinary chondrites from [15]. Solid line is analytic fit to the data.

The standard equation for hydrostatic pressure p is solved for obtaining the internal run of pressure with distance r from the centre, and the standard heat conduction equation for the run of temperature $T(r)$. Heat sources are the decay of ^{26}Al and ^{60}Fe (initial abundances $5.5\cdot10^{-5}$ and $1.6\cdot10^{-6}$ relative to ^{27}Al and ^{56}Fe, respectively, at time of CAI formation), homogeneously distributed in the body. The heat conductivity K is approximated for the porous medium by

$$K=K_b\left(\exp(-4\phi/\phi_1) + \exp(-4.4-4\phi/\phi_2) \right)^{1/4},$$

where ϕ_1 (=0.08) and ϕ_2 (=0.17) are two parameters determined from our laboratory measurements for high porosities ($\phi>0.4$) (see above) and from experimental results for ordinary chondrites [15] at lower porosities ($\phi<0.4$) (cf. Fig. 1). The conductivity of the bulk material K_b is determined as 3.3 W/mK by extrapolating the data of [15] for ordinary chondrites to zero porosity. The porosity ϕ changes in the interior of the planetesimals due to hot pressing. This is modeled by an approach similar as in [16], based on the experimental determination of creep of olivine during hot pressing [17], the model of [18] for deformation of spheres during hot pressing, and the model for sintering of [19]. The corresponding differential equation for change of ϕ

with time depends on T by an Arrhenius-like factor and on pressure p. The equation for $\phi(r,t)$ is solved simultaneously with the heat conduction and pressure equation by a fully implicit difference method.

Results and discussion: An important parameter that determines as to whether a planetesimal will differentiate or will just undergo thermal metamorphism is the peak temperature reached in the centre of the body. Fig. 2 shows a comparison of peak central temperature in planetesimals depending on their initial radius and formation time. For rocky planetesimals (porosity ϕ=0), partial melting temperatures (~1300 K) can occur in planetesimals of ~7 km radius if they form contemporaneously with CAI. If the initial porosity is 50%, the minimum radius for melting to occur is reduced to only ~4 km.

The effects of porosity are also important for understanding processes that occurred at relatively low peak metamorphic temperatures, which can be achieved in relatively small and late-formed bodies. For example, carbonaceous chondrite metamorphism corresponding to petrologic type 3 (~670-870 K, as inferred e.g. for CV or CO chondrites) can be achieved in >20 km sized porous bodies 3.0 ± 0.5 Myr after CAI, consistent with average CO chondrule ages of 1.9 ± 0.5 [9] or 2.7 ± 0.4 Myr [8] after CAIs. Likewise, aqueous alteration at temperatures between 430 and 670 K (petrologic type 2) as typical for CM or CR chondrites, can be expected 3.0 ± 0.5 Myr after CAIs for >20 km sized porous bodies, consistent with average CR chondrule ages of 3.0 ± 0.7 Myr [20-22].

Cometary parent bodies likely experienced much lower metamorphic peak temperatures that were only possible about >5 Myr after CAI (provided homogenous ^{26}Al distribution in comet and asteroid forming regions), regardless if cometary parent bodies were large or only km sized. This could imply that a - possibly substantial - fraction of earlier formed planetesimals scattered out to the Kuiper belt or the Oort cloud are comets that already burned out due to early thermal activity induced by short-lived nuclide heating.

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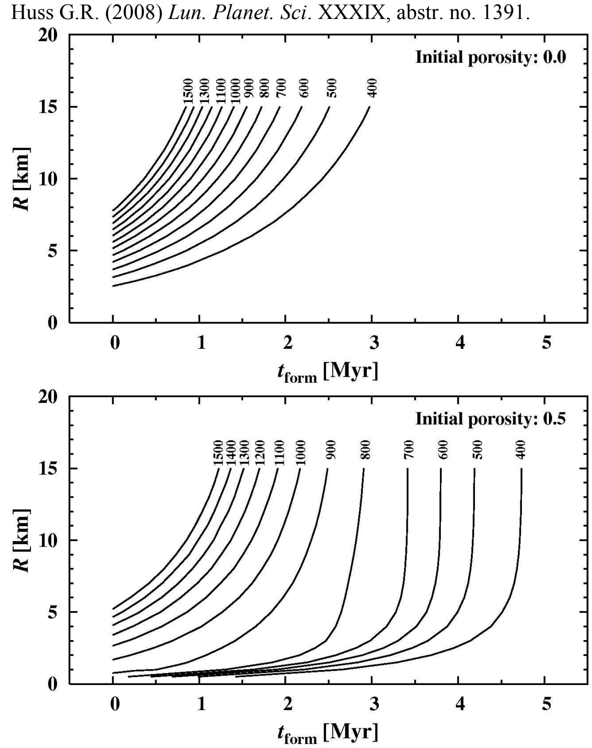

Figure 2. Comparison of peak central temperature in planetesimals depending on their initial radius and formation time. Upper panel: rocky material, lower panel: material with 50% initial porosity.

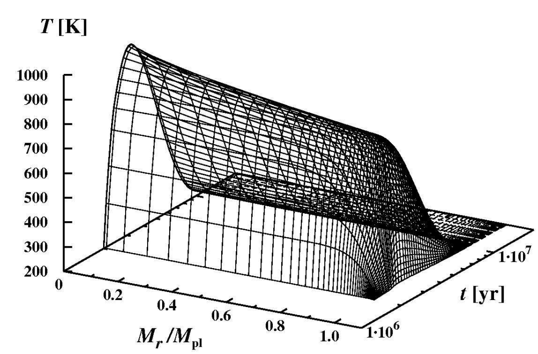

Figure 3. Temperature-time profiles at different radii from the center to its surface in a body of 10 km radius that formed 2 Myr after CAIs, initial porosity 50%.