JOINT THERMAL AND COLLISIONAL MODELING OF THE H-CHONDRITE PARENT BODY.

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Introduction. Thermal and collisional models for meteorite parent bodies can provide important constraints on the compositional, structural, and dynamical evolution of asteroids. Previous thermal modeling has constrained the diameter of the H-chondrite parent body to ~150-200 km, assuming heat generation by ^{26}Al decay in a rocky object [1-5]. This classic "onion-shell" model is characterized by peak temperature (assessed from petrographic type) increasing and cooling rates decreasing toward the more insulated center of the body. Metallographic cooling rates [MCRs; 1,6] are broadly consistent with cooling in an object of this size, but the lack of a compelling inverse correlation with peak temperature suggests either that metamorphism occurred in smaller, unconsolidated bodies that were subsequently accreted into a final parent body [7], or the rocky onion-shell parent body was collisionally disrupted and reassembled [8] prior to cooling through 500ºC, the metallographic blocking temperature. However, recent work applying Pb, Ar, and fission-track thermochronometers to selected H-chondrites has revived the concept that chondrites cooled in bodies with undisturbed onion-shell structures [4]. Here we review the cooling history recorded in these meteorites and introduce a new framework for modeling the effects of collisions on thermal evolution. We will suggest that an intermediate class of solutions may exist that exhibit features of both onion-shell and impact mixing models.

Data. In general, MCRs are uncorrelated with petrographic type for H-chondrites [6]. Recent arguments [4] that MCRs are unreliable because they have been disturbed by shock heating appear to be unfounded, as central Ni concentrations in taenite grains cannot be modified after metamorphism without destroying the cloudy taenite microstructures that are present in all chondrites with coherent MCRs. In addition, there are unshocked (S1) H3 and H4 chondrites that cooled 10-100× slower than three fast cooled H4 chondrites, severely weakening any correlation between type and cooling rate [9]. MCRs are also correlated with Ar and fission-track thermochronometers. Further arguments [4] for an onion-shell parent body focus on a direct correlation between petrographic type and Pb-Pb, Ar-Ar, and Pu fission-track cooling intervals. Larger data sets, however, do not show such simple trends and indeed part of the depicted onion-shell trend [4] depends on a controversial reclassification of Sena as H5 instead of H4. We infer that the four thermochronometers are concordant and the 7 samples used to support the onion-shell model [4] may not be representative of H-chondrites with pristine metamorphic records. The range of MCRs as a function of petrographic type is an order of magnitude greater than expected from onion-shell thermal modeling, suggesting either that onion-shell structures never existed or that such bodies were broken up and reassembled prior to cooling below 500ºC. For this preliminary report we focus on the latter.

Model. We model fragmentation and reassembly using smooth particle hydrodynamics (SPH) and an N-body gravitational code, while treating the long-term thermal evolution before and after this event using a finite-element heat transfer code.

Collision and Reassembly Model. We model the collision phase of the impact between two asteroids with the 3D code SPH3D [10], which models shock propagation in elastic solids, utilizing a plastic yield criterion for intense deformation together with an explicit fracture and dynamic fragmentation model. Gravitational self-compression of the target during the impact phase is treated as an overburden stress that must be exceeded before fracture can initiate [11]. We utilize a Tillotson equation of state model for basalt. Once the impact phase of the simulation is complete, the outcome of the SPH model is handed off as the initial conditions for the N-body code `pkdgrav` [12]. This scalable, parallel-tree code can rapidly detect and accurately treat low-speed collisions between particles, allowing for realistic modeling of the formation of rubble pile accumulations among ejected fragments. The models described here use 10,000 particles for the target, which adequately tracks 92-99% of the mass, given a power law that results from 30-70% of the mass residing in the largest fragment [13].

Thermal Model. If temperature changes due to the impact are independent of temperature just before the impact, then the thermal-evolution calculations can be completely decoupled from the collision-and-reassembly calculations. That is, a reference thermal model can be interrupted at any time with a collision; different SPH/N-body results simply provide different mappings of particle locations and associated temperatures from the initial to final body. For this preliminary work, we assume that temperatures are constant during the collision and reassembly. Representative temperature increases of ~100ºC will be recovered from the SPH model in follow-on studies. Reaccretion times are of order 10^4 s, therefore a negligible fraction of the fragments would be small enough (meter-sized or less) to lose significant heat during free fall.

Physical parameters are currently considered to be temperature-independent [2], and initial ^{26}Al/^{27}Al = 5x10^{-6} [2] corresponds to "instantaneous" accretion 2.4 my after CAI formation. A multiphysics modeling package [14] was used to solve the heat-conduction equation with a constant surface temperature of 200 K. Because the initial temperature distribution is assumed to be radially symmetric, a 1D model is used to establish the thermal state at the time of impact, but a 3D model is required to track the thermal history of the reassembled body. The 3D models had 9,000–36,000 nodes and used linear finite elements. Collision times were varied from 0.3–100 my after accretion and thermal calculations were carried out to 300 my after the collision.

Results. To date we have modeled a rocky 170-km H-chondrite parent body [2] struck by an object 20-50 km in diameter at 0º and 45º, at a speed of 5 km/s. Figure 1 shows the results of the head-on impact of a 32-km dia object. The reassembled parent body (140 km dia or 56% of the initial mass) shows distinct thermal structure, because the impact is not a random mixing process. Time-temperature histories of 100 randomly selected nodes vary widely, showing both post-reaccretion heating of formerly cool parcels and rapid cooling of hot material. Even unshocked H-chondrites show large scatter in metallographic cooling rates at 500ºC; the fragmentation-and-reassembly model has a comparable distribution—a feature onion-shell cooling models cannot reproduce.

Conclusions. This report demonstrates the potential of the combined 3D SPH/N-body/thermal evolution approach to model statistical distributions of meteorite peak temperatures and cooling rates. Even from this preliminary work, it is evident that fragmentation and reassembly may not impose complete randomness, but instead develops thermal histories intermediate between an onion shell and random mixing. Therefore it may not be surprising that cooling-rate measurements of the least disturbed samples lead to the inference of onion-shell structure [4] whereas the majority of H-chondrites may point to a more complex history [7,8].

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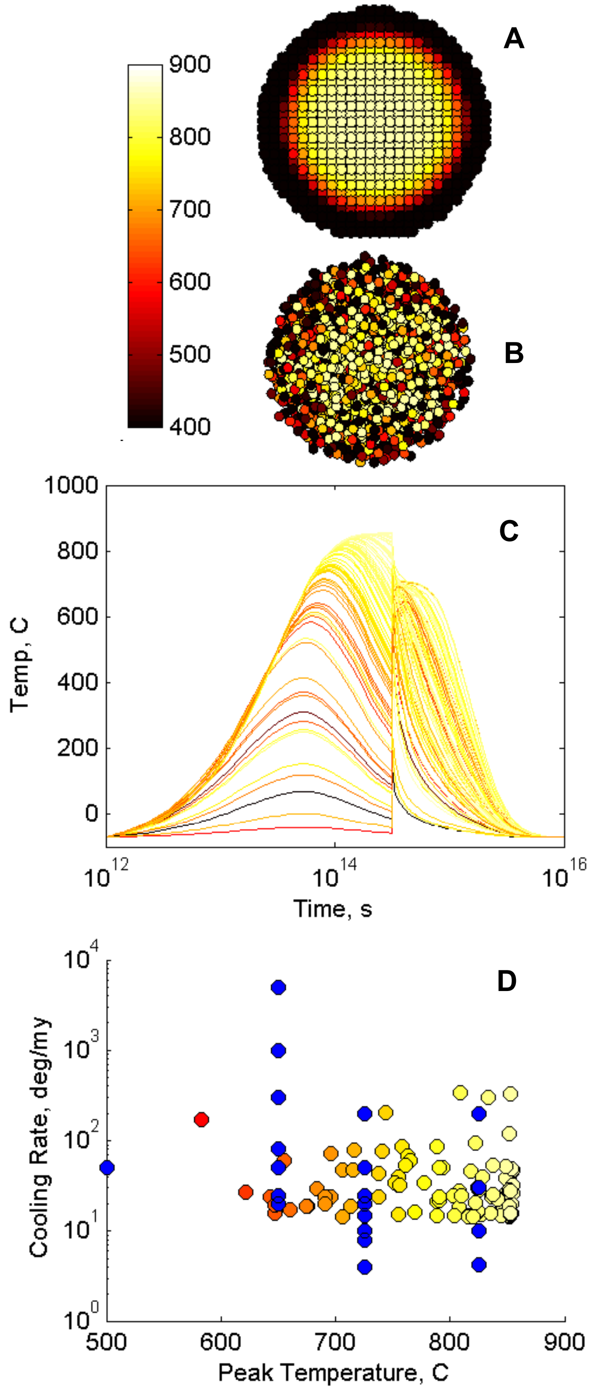

Figure 1. Temperature cross-sections of model parent body before (A) and after (B) collisional disruption and reassembly 10 my after accretion. Time-temperature histories (C) are complex. Cooling rates at 500ºC (D) show scatter comparable to data for unshocked H-chondrites (blue) that onion-shell cooling stucture alone cannot reproduce.