Asteroid Thermal Evolution with Fragmentation and Reassembly into a Rubble Pile. Jialong Ren[1], Marc A. Hesse[1], Michael P. Lucas[2] and Nick Dygert[2], [1]Department of Geological Sciences, University of Texas at Austin (jialongren@utexas.edu), [2]Department of Earth & Planetary Sciences, University of Tennessee, Knoxville.

Introduction: A large body of work has come to the conclusion that ordinary chondrite (H, L, and LL) parent bodies accreted rapidly and then experienced decay heating followed by slow cooling, without further disruption [e.g., 1]. This so-called onion shell model has been challenged by recent geochemical observations showing that these bodies cooled rapidly from near peak temperature [2]. Together with previous evidence for slow cooling at lower temperatures [e.g., 3], this suggests that these bodies experienced catastrophic fragmentation near peak temperature and quickly reassembled into rubble pile asteroids.

To test this hypothesis we have developed a thermal model for asteroids with fragmentation and reassembly into a rubble pile. In particular, we want to test if the fast, high-temperature cooling rates can be reconciled with the slow, low-temperature cooling rates [3]. Here we focus on the development of a model for samples from the H chondrite parent body.

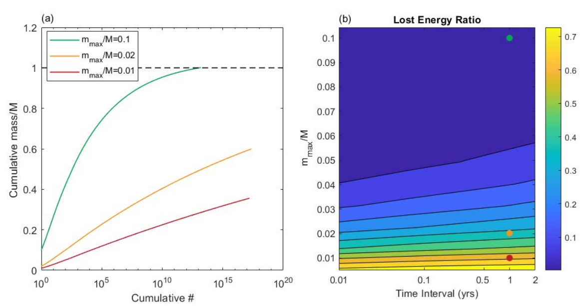

Figure 1. (a) The cumulative mass to total mass ratio as a function of cumulative fragments number of a 100 km radius initial body. The green curve ends when it recovers 99.9% of the initial mass, and the other two curves end when the mass of the smallest fragments is smaller than 1 kg. **(b)** Energy loss ratio during fragmentation as function of both the largest fragments mass and total mass ratio m_{max}/M and reassembly time interval.

Models: The thermal model consists of three stages: the heating of the initial body, the cooling of fragments, and the evolution of the reassembled rubble pile. The initial body is heated by the decay of short-lived radionuclides until it is catastrophically disrupted. Here we assume this fragmentation happens at the peak central temperature according to [2]. To model fragmentation and fragment thermal evolution we combine a fragment mass distribution equation with analytic solutions to estimate fragment cooling. We take the form of a well-established power-law for mass distributions after impacts [4,5] and rewrite the relationship between the power-law parameters and the mass fraction of the largest fragment to the total mass m_{max}/M discreetly. Fig. 1a shows the relationship between the fragments numbers and the cumulative mass for different levels of fragmentation.

As shown in Fig. 1b, the energy loss mainly depends on the fragmentation extent, within a possible reassembly time interval range [6], and only the most extreme fragmentations lead to significant energy loss.

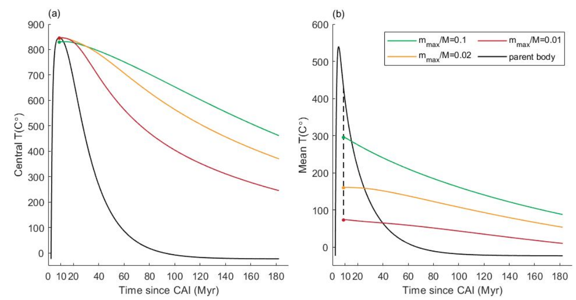

Figure 2. (a) Central temperature history of the undisturbed parent body (100 km radius) and reassembled rubble piles for three different fragmentation levels. **(b)** Average temperature history.

In the third stage, we assume that all fragments reassemble into a single rubble pile instantaneously, and the largest fragment forms the nucleus while the smaller fragments accrete onto it as spherical shells ordered by mass. This leads to a rubble pile with a hot core surrounded by a thick mega-regolith that forms a cold and more porous shell.

We assume that the hot core has the same porosity (0.1) as the fragments, but the cold outer shell has a larger porosity of 0.2, which starts from 0.5 radius of the rubble pile. We use the relationship between thermal conductivity and porosity from [7].

Result: The overall evolution of a 100 km body accreted at 2.27 Ma after CAI, fragmented at peak temperature and reassembled into a rubble pile is shown in Fig. 2. We consider three different extents of fragmentation, set by the ratio of the largest fragment to the total body. Panel a shows that the central temperature is not strongly affected by the fragmentation, because we assume the largest fragment forms the core of the rubble pile. Panel b shows that the mean temperature, which is proportional to the total energy of the body, drops during fragmentation. The more intense the fragmentation the higher the energy loss. This is also shown in Fig. 1b, where colored dots indicate the three model runs shown in Fig. 2. However, despite the energy loss during fragmentation, the re-accreted rubble pile retains energy longer than the undisturbed planetesimal. This is due to the insulation provided by the increased porosity. These simulations demonstrate that fast, high-temperature cooling rates can be reconciled with the slow, low-temperature cooling rates.

Next we consider the particular case of the H chondrite parent body. The purpose of our modelling is not to reproduce an exact evolution history of the H chondrite parent body, but to test that the large discrepancies in cooling rates observed in samples can be reproduced by our model. In this particular case, we investigate a 100 km radius initial body in which the decay of ^{26}Al is the only heat source. We assume the peak central temperature is 846 °C and the fragmentation happens when the center is at its peak temperature [2] . The initial accretion time (2.27 Ma) and fragmentation time (8.77 Myr) are determined from the peak temperature constraint. For the fragmentation, we assume m_{max}/M is 0.01, and the mass or energy introduced by the impact is not considered.

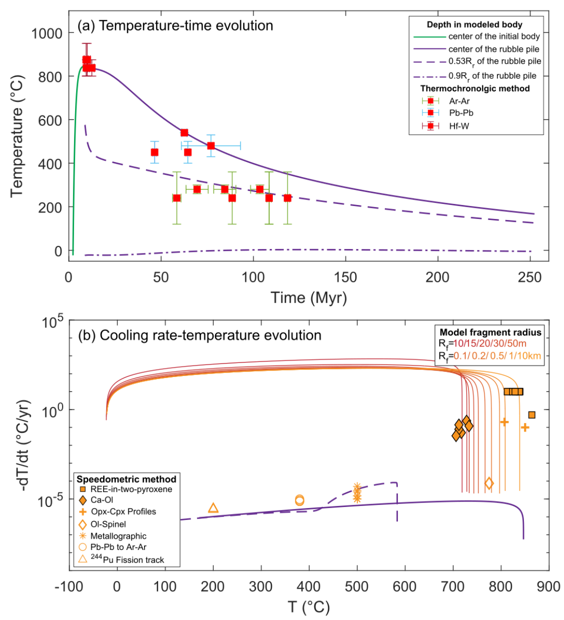

Figure 3. Thermal evolution simulation for fragmentation and reassembly of the H chondrite parent body [2]. Model parameters are radius R=100 km, accretion time, t_{acc}=2.27 Myr after CAI formation, fragmentation time, t_{frag}=8.77 Myr after CAI formation, and reassembly into a rubble pile after dt=1 yr. Fragmentation parameter is m_{max}/M=0.01 and porosity of the megaregolith of the reassembled rubble pile is 0.2. **(a)** Temperature evolution of parent body and reassembled rubble pile in comparison with thermochronological data. **(b)** Cooling rate of fragments (orange) and rubble pile (purple) as functions of temperature and comparison with cooling rate data from H6 chondrites. The curves for the fragments represent the lower bound on cooling rates.

The results of our simulation are shown in Fig. 3, together with available cooling rate data. Fig. 3a shows the temperature evolution at several depths within the rubble pile, which is broadly consistent with available thermochronological data. The 0.9R_r curve shows that the megaregolith experiences reheating due to conduction from the hot core.

Fig. 3b shows the cooling rates as a function of temperature for both the fragments and the rubble pile. The orange curves represent the slowest cooling rates of fragments with different sizes. These curves demonstrate that a fragment cannot cool past any temperature with an arbitrary low cooling rate within a given time interval (1 year in this case). It is not surprising that the observed fast cooling rates at high temperature can be reproduced by our fragmentation model.

More interesting is the ability of the model to reproduce the slow cooling rates at low temperatures. The purple lines represent calculated cooling rates at different depths in the re-assembled rubble pile. They are consistent with available cooling rates from metallography, Ar-Ar and Pb-Pb ages, and fission-track data.

Discussion: Our model shows that fast, high-temperature cooling rates can be reconciled with the slow, low-temperature cooling rates. This makes fragmentation and reassembly a viable model for the thermal evolution of the H chondrite parent body as well as others that have experienced similar cooling histories. If such histories of fragmentation and reassembly can be established for other parent bodies, it would indicate a more dynamic early solar system.

Our model also demonstrates the counterintuitive conclusion that fragmentation and reassembly into a rubble pile lead to long-term energy retention. In other words, the energy initially lost during fragmentation is later recovered due to the insulating mega-regolith. As such, fragmentation and reassembly help to explain the surprisingly warm thermal state of several heat starved bodies.

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