THE ENERGY BUDGET OF PLANETESIMAL COLLISIONS: A QUANTITATIVE ANALYSIS Thomas M. Davison[1,2], Gareth S. Collins[2], Fred J. Ciesla[1] and David P. O'Brien[3]. [1]Department of the Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago, IL 60430, U.S.A. [2]Impacts and Astromaterials Research Centre, Dept. of Earth Science and Engineering, Imperial College London, London, SW7 2AZ, United Kingdom. [3]Planetary Science Institute, 1700 E. Ft. Lowell, Suite 106, Tucson, AZ 85719, U.S.A. (E-mail: thomas.davison02@imperial.ac.uk).

Introduction: The source of heating in planetesimals in the early Solar System has still not been fully quantified. The decay of short-lived radionuclides such as ^{26}Al undoubtedly provided large amounts of energy to heat planetesimals. Impact generated heating has also been discussed as an important heat source [1-3]. Recent work has suggested that planetesimals were likely to have accreted with high porosities [e.g. 4-6]. Numerical modeling has shown that collisions between porous planetesimals could have generated significant additional heating [7]. However, the available heating from each of these sources has not yet been directly compared — numerical modeling of planetesimal collisions will allow us, for the first time, to compare the available energy from planetesimal collisions with heating from short-lived radionuclides.

Statistical model: A novel Monte Carlo model was developed in order to assess the amount of heating produced by impacts throughout the initial 10 Ma period of Solar System history. Each simulation modeled the collisional histories of many thousands of parent bodies. Two sizes of parent bodies were modeled: 100 km and 500 km in diameter. Parent bodies were assumed to have an ambient temperature of 300 K and a porosity of 50%. Heating by ^{26}Al was neglected to allow the effects of impacts to be independently assessed. For each parent body, collisions were allowed to occur on the surface until either the parent body was catastrophically disrupted, or 10 Ma of time had passed. In each collision event, the collision velocity and impactor size were determined from velocity- and size-frequency distributions of colliding planetesimals extracted from N-body simulations [8-10]. The mass of material heated to several temperatures (400 K, 700 K, 1000 K, the solidus and the liquidus) during each collision was determined from numerical modeling of porous planetesimal collisions using the iSALE hydrocode [7]. Two disruption criteria were compared: First, a simple criterion based on the observation that, for a range of small bodies in the Solar System, impact craters with diameters much larger than the radius of the target body are not observed [11]; and second, a criterion based on numerical simulations of collisions between porous bodies [12, 13], which allows for larger and/or faster impactors than the observation-based criterion. Simulations were run for two impactor population mass (M_{pop}), 100 and 1000 times the mass of the present day asteroid belt.

Results: To analyse the results of the Monte Carlo model, the parent bodies were split into two populations: those that survived to 10 Ma without being disrupted, and those that were disrupted. The probability of disrupting a parent body depended on the total mass of the impacting planetesimal population, the disruption criterion and the size of the parent body.

In general, if a parent body was not disrupted, global heating of the body was not possible — heating would remain local to the impact site. Typically, $\ll 10\%$ of the mass of non-disrupted parent bodies was heated to the solidus. Using the most conservative assumptions of the disruption criterion (observation-based criterion) and the impacting population mass (M_{pop} = 100), it was estimated that, on average, one twenty-thousandth of the parent body was heated to the solidus; the most generous assumptions (modeling-based disruption criterion; M_{pop} = 1000) suggest that, on average, approximately one hundredth of a surviving parent body was heated to the solidus (Fig 1a). However, in some cases ($\sim$ 0.5%

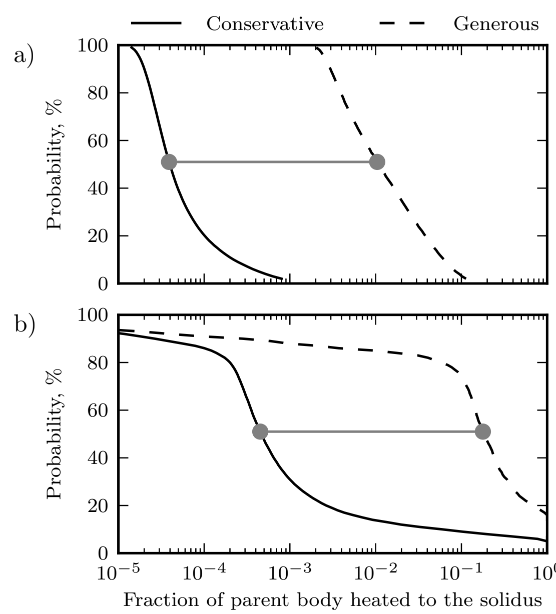

Figure 1: *Results from Monte Carlo simulation: Probability of heating a given fraction of the parent body to the solidus, in a) those parent bodies that were not disrupted before 10 Ma, and b) those parent bodies which were disrupted in that time period. Shown are the estimates based on the most conservative assumptions of disruption criterion and impacting population mass (solid line) and the least conservative assumptions (dashed line).*

of parent bodies), it was possible for ~ 3–4 events to occur that could have heated 5–10% of the parent body to the solidus without disrupting the body. The most important unconstrained parameter for determining the mass of heated material in a surviving parent body was the mass of the impacting population — more impactors would have led to more collisions, and hence more heating.

For those parent bodies that were disrupted, typically much more heating was produced when compared with those that did not disrupt; in some cases global heating was possible. The majority of heating occurred in the final, disruptive collision. Using the most conservative assumptions of the disruption criterion and the impacting population mass, the model predicted that, on average, a disrupted parent body had approximately one thousandth of its mass heated to the solidus; using the least conservative assumptions, it was predicted that, on average, more than one fifth of the parent body was heated to the solidus in the disruptive collision (Fig 1b). The most important unconstrained parameter determining the amount of heating during disruption is the catastrophic disruption criterion.

Discussion: The simulations described above show that collisional heating can be very localised to the impact site, perhaps explaining the heterogeneous heating observed in some meteorites [e.g. 14]. In order to determine the significance of this heat in comparison with the decay of short-lived radionuclides, the increase in the specific internal energy associated with collisional heating on a parent body was determined.

For each collision simulated in the Monte Carlo model, the increase in internal energy was calculated by: (a) determining the mass of material raised to several shock pressures from hydrocode simulation results [7]; and (b) using the equation of state and the Hugoniot shock relationships for dunite to compute a specific internal energy increase associated with each of these shock states.

The average increase in specific internal energy due to collisions in the first 10 Ma was determined: First, the total increase in internal energy from all impacts on each parent body was calculated. To convert this to a specific internal energy increase, the energy was divided by the total mass of the target planetesimal. Second, the average increase of specific internal energy over the 10^5 parent bodies simulated in the Monte Carlo model was calculated. At the same time, the specific internal energy increase due to each impactor size bin was also determined (Fig. 2). This calculation reiterates that the vast majority of energy comes from the few large impactors ($\gtrsim$ 50 km radius), rather than the many collisions by smaller projectiles ($\lesssim$ 10 km radius).

Outputting this data from the Monte Carlo model at frequent time intervals gives a quantitative measure of the heating available from planetesimal collisions through time. By calculating the available energy budget from short-lived radionuclide decay [e.g. 15, 16], we will present a comparison of these two important heat sources. This will provide a complete picture of how primitive material was heated by the complimentary sources of radioactive decay and impacts.

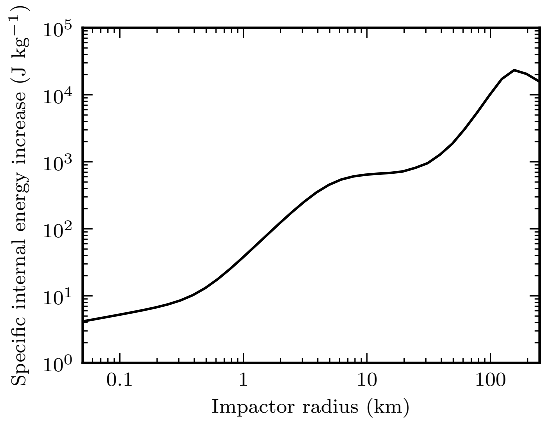

Figure 2: *Average increase of specific internal energy per impactor size bin, after 10^5 parent bodies were modeled in a Monte Carlo simulation. The impactor population mass was 1000 times the mass of the present day asteroid belt. Impactor size bins are spaced logarithmically. The majority of energy comes from the few collisions with the largest impactor sizes (> 50 km), rather than the many collisions with impactors in the smaller size bins (< 10 km).*

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