NUMERICAL SIMULATIONS OF SUB-CATASTROPHIC POROUS PLANETESIMAL COLLISIONS

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Introduction: Porosity is an important property of many small solar system objects. The bulk density of some asteroids and comets suggests that pore space may occupy as much as 60-80% by volume [e.g., 1,2]. Moreover, as planetesimals are expected to form via gentle aggregation of smaller bodies, the first generation of large solid bodies likely possessed significant (>50%) porosity [3-5].

It has long been known that porosity has a strong influence on shock wave attenuation and shock heating in hypervelocity impacts [6]. The compaction of a substantial volume of pore space can dramatically decrease the peak shock pressure and increase the post-shock temperature of impact-processed materials. Hence, pore collapse may play a major role in disruption, melt and vapor production, momentum transfer and crater formation, when solar system bodies collide.

Addressing the influence of porosity on impact heating, Davison et al. [7] demonstrated that impacts at speeds greater than 4 km/s could cause significant localised heating on planetesimals if they were porous. Statistical models [8], based on these results, suggest that impact heating may be an important secondary heat source in the early solar system (in addition to the decay of short-lived radionuclides), with most heat delivered to a surviving planetesimal in large sub-catastrophic collisions (i.e., collisions in which just over half the original planetesimal mass is retained). Critical to understanding the importance of impact heating in the early solar system, therefore, is quantification of (a) the disruption threshold for weak, porous first-generation planetesimals; (b) the evolution of planetesimal porosity with time through impact-induced compaction; and (c) the redistribution and retention of heated material in sub-catastrophic collisions. Here we extend the work of [7,8] by simulating large sub-catastrophic planetesimal collisions to late times, quantifying global compaction as well as the ejection and redistribution of impact heated material.

Methods: We used the 2D iSALE hydrocode [9,10] to simulate sub-catastrophic head-on collisions between porous planetesimals. ANEOS-derived equation of state tables for dunite were used to represent the thermodynamic response of non-porous planetesimal material. Pore-space compaction was modeled using the improved epsilon-alpha porosity model [9,11]. Material strength was modeled using the procedure described in [10] with parameters for weak rock. The target planetesimal was 500 km in diameter with a uniform initial temperature (300K) and porosity (50%). Impacting planetesimals of 50-150 km in diameter and with identical material properties to the target collided with the target at 4-7 km/s.

The gravity field was updated periodically during the calculation using a self-gravity algorithm, inspired by [12], implemented and tested for the purposes of this study. During a gravity update the gravitational attraction of cells containing mass (actually rings of mass due to axial symmetry) is calculated for each vertex of the mesh. Computational efficiency is achieved with minimal loss of accuracy by combining cells into patches of 2×2/4×4/8×8/etc neighbouring cells when they are sufficiently far from the point of interest and computing the gravitational acceleration of the patch (ring) as a whole. The size of the patch h is determined by a user-defined accuracy parameter, the opening angle θ, times the distance l between the patch center and the vertex at which gravity is being computed, $h = \theta l$ [12]. Thus, large numbers of cells are combined to form massive patches (rings) when accounting for the gravitational acceleration of mass far from the point of interest. The algorithm was tested against benchmark problems discussed in [13].

Results: The compaction of pore space during a planetesimal collision increases shock heating and reduces ejection velocities relative to the non-porous case (Fig. 1). Hence, if planesimals are sufficiently porous, collisions can cause substantial heating and, even in large sub-catastrophic collisions, the vast majority of the heated material is retained on the target planetesimal.

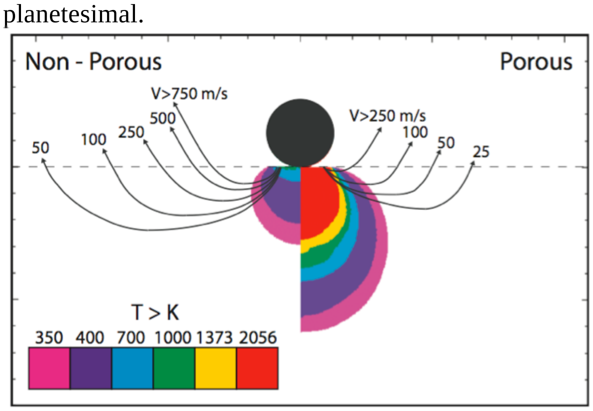

Figure 1 Provenance of shock heated material from a 7 km/s impact on a porous (right) and non-porous (left) 500-km diameter target planetesimal. Material above each vertical velocity contour (solid back line) is ejected from the planetesimal surface at a velocity greater the value indicated. Note that in the porous target case a much larger volume of the target is heated, whilst a smaller volume is ejected faster than escape velocity (250 m/s).

Figure 2 shows results from a simulation of a 125-km diameter planetesimal impacting a 500-km diameter target planetesimal at 4 km/s (both bodies have an initial porosity of 50%). In this example, the collision is below the threshold for catastrophic disruption, but nevertheless affects the entire target planetesimal. On the impacted side of the planetesimal a deep crater is excavated and then collapses so that the hot, compacted material forms a deep plug beneath the crater floor.

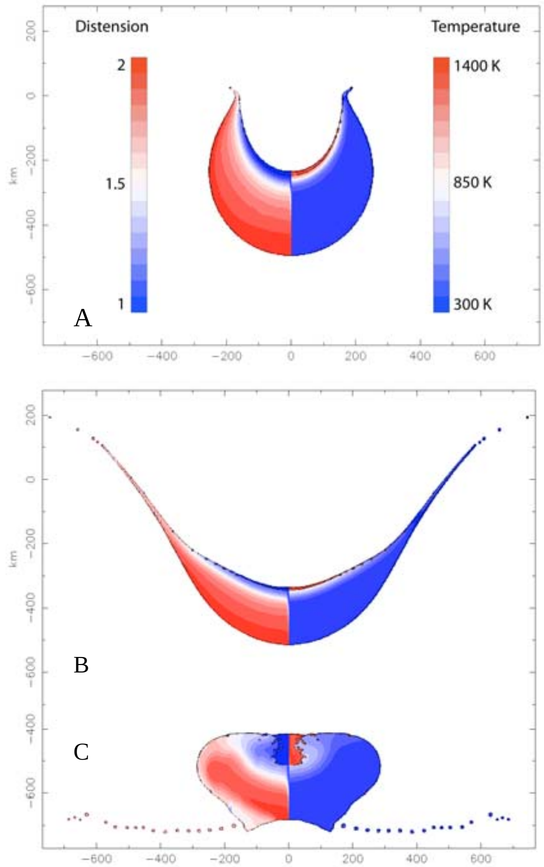

Figure 2 Temperature (right) and distension (left) at three times during a 4 km/s collision between two porous planetesimals (the intial distension is 2—50% porosity—and the initial temperature is 300 K). (A) After 4 minutes, shock wave propagation has compacted and heated proximal material, fractured the entire target body and excavated a large crater. (B) After 35 minutes, the floor of the crater has stopped growing and is lined by hot, compacted material, whilst ejecta begins to return; the cratering process has deformed the entire planetesimal (C) After 180 minutes, the impacted side of the planetesimal is modified as hot, compacted material collapses into the crater, whilst ejecta lands on the rear side causing secondary compaction.

On the rear side of the planetesimal, ejecta from the crater lands energetically, causing secondary compaction near the surface. More than 15% of the pore space in the target planetesimal is compacted during the collision; only the rear-side interior is uncompacted.

Similar models of impactors up to 150-km in diameter are all sub-catastrophic, suggesting that the impactor size required to catastrophically disrupt the target body is greater than 150 km in diameter. This is consistent with the predicted disruption threshold for porous bodies [14] and larger than the predicted threshold for weak non-porous rocks [15]. In the case of a 150-km diameter impactor, less than 10% of the colliding mass is accelerated to speeds exceeding the escape velocity of the target body and more than 20% of the pore space in the target planetesimal is compacted during the collision.

Simulations of a 50-km diameter impactor show that this is well below the disruption threshold: negligible mass is ejected at speeds greater than escape velocity. In this case, a large crater forms on one side of the target, underlain by compacted and heated material, but deformation is restricted to the impacted hemisphere of the planetesimal. Only 1% of the target volume is compacted by the shock wave.

Conclusion: Large sub-catastrophic collisions between porous planetesimals at speeds greater than 4 km/s can generate significant volumes of heated material that is retained on the surviving planetesimal. The heated material is localized within the impacted hemisphere, forming a deep plug beneath the impact site. Secondary compaction occurs across the surface of the rear-side, which reduces the potential for subsequent impacts to further heat the planetesimal.

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