MESOSCALE MODELLING OF IMPACT COMPACTION OF PRIMITIVE SOLAR SYSTEM SOLIDS

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Introduction: Primitive solar system solids are expected to have accumulated as bimodal mixtures of mm-scale zero-porosity inclusions (chondrules) surrounded by highly porous, sub-μm dust particles (matrix). Previous numerical simulations of the impact processing (e.g., compaction and heating) of such materials have treated the mixture as homogeneous and estimated impact-generated bulk shock pressures and temperatures over large (i.e., planetesimal) scales [e.g. 1, 2]. Here we show that modelling bimodal mixtures explicitly and resolving the shock response on the scale of individual chondrules requires a different numerical approach (mesoscale modelling [e.g. 3]). Our models reveal a very heterogeneous response to shock with important implications for interpreting the meteoritic record.

Modelling: We have developed a method for simulating the mesoscale compaction of early solar system solids in low velocity impact events [4, 5], using the iSALE shock physics code [6–8]. Chondrules were represented by nonporous disks, placed within a porous matrix. Chondrules and matrix were represented by the ANEOS equation of state for dunite/forsterite [9]; in some simulations the matrix was represented by the ANEOS equation of state for serpentine [10]. Matrix porosity was varied between 60 and 80%, initial matrix fraction between 30 and 80%, and impact velocity between 0.75 and 3km s^{-1}. By simulating impacts into bimodal mixtures over this wide range of parameter space, we show how each parameter influences the shock processing of heterogeneous materials [5].

Results: Our mesoscale models produce post-shock material consistent with bulk porosity and chondrule-to-matrix ratios of different meteorite groups (such as carbonaceous chondrites and unequilibrated ordinary chondrites), depending on the initial conditions, and reveal the following insights:

Temperature dichotomy: One key result is that the temperature after shock processing shows a strong dichotomy: matrix temperatures are elevated much higher than the chondrules, which remain largely cold. For example, in an impact at 2 km s^{-1} into a mixture of 70% matrix and 30% chondrules, with a matrix porosity of 0.7, the matrix was elevated from 300 K to 1100 $\pm$ 110 K, while the chondrules were only heated to 367 $\pm$ 45 K.. Using a simple 1D finite difference calculation to solve the heat conduction equation, we found that this temperature dichotomy would have been short lived; the timescale for the temperature equilibration is highly dependent on the porosity of the matrix after the shock, and will be on the order of seconds for post-shock matrix porosities of less than 0.1, and on the order of 10's to 100's of seconds for matrix porosities of $\sim$ 0.3–0.5.

Matrix compaction: Chondrules can protect some matrix from shock compaction, with shadow regions in the lee side of chondrules exhibiting higher porosity that elsewhere in the matrix. In simulations with low initial matrix-to-chondrule volume ratios, and at velocities high enough for chondrules to come into contact with each other, the porous matrix was shielded from the shock effects by stress bridges between chondrules, and was thus compacted less.

Matrix composition: Changing the matrix composition to serpentine from forsterite had two important effects. First, for an equivalent to shock pressure, there was more compaction of the serpentine matrix than of the forsterite matrix. Second, the temperature increases in the serpentine matrix were consistently lower than in the forsterite matrix, for impact speeds fast enough to produce a shock pressure high which was high enough to trigger a phase change in the water component of the serpentine. This phase change acted to buffer the temperature increase.

Discussion: Using these results, it is possible to constrain $\varepsilon - \alpha$ porous compaction model [8, 11] parameters suitable to describe the bulk-material response in macroscale simulations of planetesimal collisions (i.e. when individual chondrules are too small to be resolved). We found that the compaction-rate parameter κ should vary with initial matrix abundance or bulk porosity ϕ_{bi} (assuming an initial matrix porosity of 0.7): $\kappa = \min(0.98, 0.21\phi_{bi} + 0.88)$.

Our observations have implications for the meteorite record: For example, since high matrix temperatures can be achieved at relatively low shock pressures, lithification of primordial materials may have been a natural outcome of the transient collisional heating of matrices, without leaving macroscopic shock indicators as evidence of the impact.

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