

PRODUCING CHONDRULES IN THE OUTER SOLAR SYSTEM: THE EFFECT OF ICE ON IMPACT JETTING.

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Introduction: Chondrules are previously molten, mm-sized droplets lodged within chondritic meteorites. The observed nucleosynthetic isotope differences between carbonaceous and non-carbonaceous chondrites have been interpreted to represent inner and outer solar system (SS) isotopic reservoirs separated by a proto-Jupiter [1, 2]. If correct, this implies that chondrules formed in the inner and outer SS. It was recently shown that the process of impact jetting is capable of producing chondrules during relatively low velocity collisions between rock bodies [3]. During impact jetting, small quantities of highly shocked, molten material are ejected from the region of impact at high speeds, forming droplets that cool at rates consistent with chondrule observations [3]. Recent pebble accretion models that successfully simulate the accretion of the giant planets show that there is abundant opportunity for large impacts in the outer SS, suggesting that such impacts may be an important chondrule formation mechanism there [4]. In this work, we simulate impacts between planetesimals of mixed ice and rock composition to show that impact jetting is capable of producing chondrules in the outer SS during the accretion of giant planet cores.

Methodology: In this work we use the iSALE shock physics code [5-7] to model a 10 km diameter projectile vertically impacting a flat target of the same composition, for a variety of compositions and impact velocities. The resolution of each model is 400 cells per projectile radius. To emulate outer SS bodies, we use iANEOS to create the equations of state (EOS) for mixtures of dunite and fractions of water ice ranging from 10-30% by mass, in 10% increments. The EOSs assume an intimate mixture of the ice and rock following the approach of ref [8]. We simulate impacts for each substance with impact velocities of 3, 4, 5, 7 and 10 km s⁻¹. The Lagrangian tracer particles utilized by iSALE allow us to track the position, velocity, temperature, and entropy of material throughout the simulation. Since we are using mixed material EOSs, it is necessary to consider the entropy of each material to determine the total amount of potentially chondrule forming material.

Results and Discussion: Although the EOSs are for mixed materials, we analyze the entropies of the

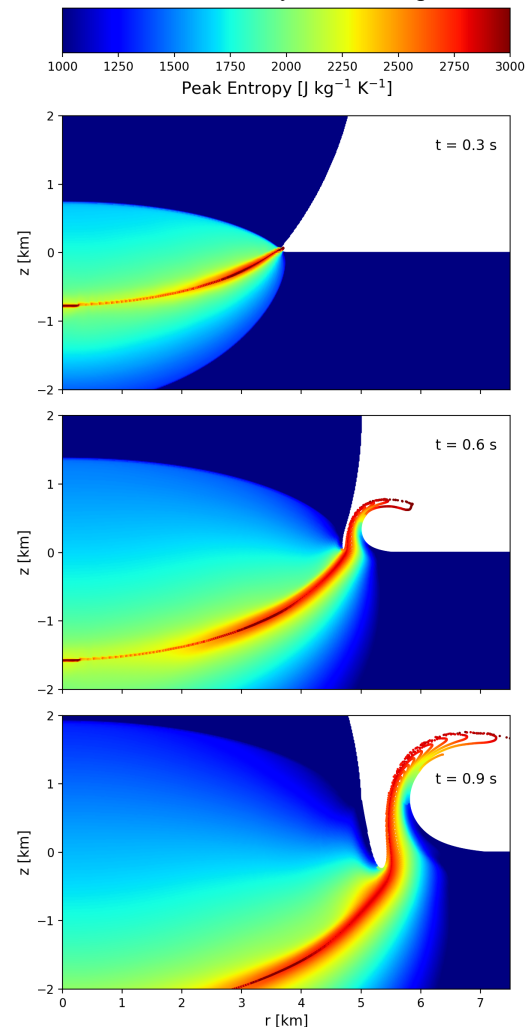


Figure 1: A time series of a mixed dunite and 10% ice by mass projectile impacting a flat target of the same composition at 5 km s⁻¹. Tracers are colored by the peak entropy of dunite. The entropy of incipient melt for dunite is 3000 J kg⁻¹ K⁻¹. Jetting is about to begin at 0.3 s, a jet has formed by 0.6 s, and the jet is overtaken by normal ejecta by 0.9 s. In this impact, ~0.03% of an impactor mass of jetted melt is produced. For a dunite impactor striking a dunite target at 3 km s⁻¹, ~1% of an impactor mass of jetted melt will be produced [3].

rock and ice separately to determine the amount of molten rock generated. This is because ice vaporizes at lower peak shock pressures than dunite, so the total entropy of the mixed material is not representative of the dunite portion relevant to chondrule formation.

Figure 1 shows the evolution of the peak entropy of dunite during the impact of a body composed of dunite and 10% ice by mass at 5 km s^{-1} , onto a flat target of the same composition. The vaporization of ice also causes expansion of the jet. In the models this expansion results in areas of low tracer density, which are visible in the last two panels of Figure 1. The presence of water vapor within the jet may cause aqueous alteration and exchange of oxygen isotopes within these chondrule melts that would not occur in melts formed from ice poor precursor materials [9].

Lagrangian tracer particles above the incipient melting entropy of dunite ($3000 \text{ J kg}^{-1} \text{ K}^{-1}$) [10] count toward the total amount of potentially chondrule forming material produced in the simulation. Tracers with a velocity greater than the impact velocity are considered to be jetted. Figure 2 shows the calculated masses of potentially chondrule forming material, rocky material with velocities exceeding the impact velocity and entropy greater than $3000 \text{ J kg}^{-1} \text{ K}^{-1}$ for each model, normalized by the mass of the impacting body.

For a dunite impactor striking a dunite target at 3 km s^{-1} , $\sim 1\%$ of an impactor mass of jetted melt will be produced [3]. The addition of ice to dunite for a 3 km s^{-1} impact represses the production of melt so that no chondrule material is formed. Figure 2 shows that ice greatly limits the amount of jetted silicate melt in the other models as well. Jetting is known to become less efficient with increasing impact velocities [11], but the production of melted material will increase with higher impact velocities due to increased shock pressures. As shown in Figure 2, the amount of melted and jetted material peaks for models with 7 km s^{-1} impact velocities, as a result of the counteracting effects. We find that the model of dunite and 10% ice by mass impacting at 7 km s^{-1} produced 0.04% of an impactor mass in chondrule forming material, about $7 \times 10^{11} \text{ kg}$. Notably, the least efficient model with 30% ice content and an impact velocity of 4 km s^{-1} still produced around $1 \times 10^{10} \text{ kg}$ of molten silica droplets, indicating that jetting can still produce chondrules in spite of relatively high ice contents.

In future work we may explore the effects of pre-impact porosity and oblique impact angles on chondrule formation. While the compressibility of more porous materials decreases the efficiency of jetting [3] it may increase material temperature and

fraction of silicate melt. Oblique impacts have been shown to increase the efficiency of jetting [12] and are statistically more likely to occur than vertical impacts.

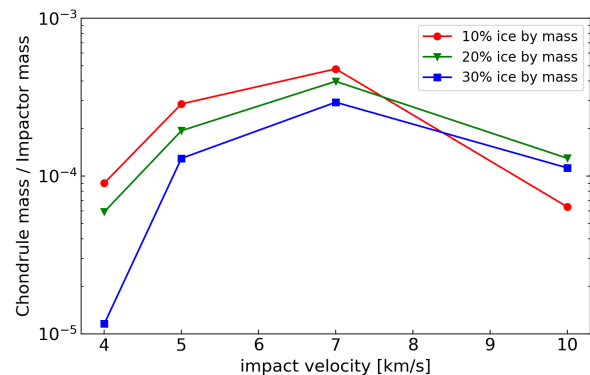


Figure 2: The mass of chondrule forming material normalized to the impactor mass for models used in this work with impact velocities above 3 km s^{-1} . For these models, an appreciable amount of chondrule material is created even for high ice contents.

Additionally, we plan to combine these impact models with the results of a LIPAD simulation of the accretion of giant planets in the outer SS [4]. These simulations will provide the details (size of bodies involved, impact velocity, obliquity, etc.) of each impact that occurs during the accretion of the rocky cores. The results of LIPAD combined with iSALE models will allow us to estimate the total mass of chondrules formed at any point in the history of the accretion of giant planet cores.

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