CHONDRULES AS BYPRODUCTS OF GIANT PLANET FORMATION.

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Introduction: The formation of chondrules, the enigmatic igneous mm-sized spherules found in chondrites, is critical to understanding the dynamics of our early solar system and the formation of planetary systems in general. Recent modeling work has determined that impact jetting during accretionary impacts may be a viable mechanism for producing chondrules [1], even in the outer solar system where planetesimals are expected to have been composed of ice-rock mixtures [2]. Impact jetting occurs during the first moments of contact between impacting bodies and requires very high resolution to model. For vertical impacts between rocky bodies, a chondrule mass ~1% of the impactor mass may be formed by jetting. This number decreases with the addition of ice to the bulk composition of impacting bodies (e.g., for bodies composed of dunite mixed with 30% ice by mass, a chondrule mass ~0.001% of the impactor mass may be generated). An estimate of cumulative chondrule mass produced by impact jetting during planetary accretion in the inner solar system has been presented in [1] by evaluating chondrules formed in each impact that occurs during GAME simulations of terrestrial planet accretion. The models for accretion of giant planets in the outer solar system differ significantly from standard planetesimal accretion models that describe terrestrial planet formation. Namely, the accretion of giant planet cores of ~10 $M_\oplus$ is more accurately described by pebble accretion models [e.g., 3]. In this work we synthesize results from pebble accretion models of giant planet core formation with impact models of ice-rock bodies in order to present an estimate of cumulative chondrule mass formed in the outer solar system.

Methods: The iSALE2D shock physics code was used to perform simulations of impact jetting during collisions of bodies with mixed ice and rock compositions. In each iSALE model, a 10 km diameter projectile impacts a flat target at impact velocities ranging from 2–7 km/s, in increments of 0.5 km/s. The projectile and target match in composition for a given mixture of ice and dunite. The mass fraction of ice mixed with dunite ranges from 0–50% ice by mass, in increments of 10%. The mass of chondrule forming material is estimated by considering material that is at least partially molten (i.e., has a peak entropy greater than the incipient melting entropy of dunite, 2371 J/kg/K) and jetted above escape velocity. We calculate how the mass of chondrules changes based on escape velocity by considering ratios of impact velocity to escape velocity, or velocity fractions, from 0.5 to 3. The LIPAD code is used to simulate accretion of giant planet cores in the outer solar system and track all the collisions occurring. The initial conditions for this simulation match those presented in [3]. For each accretionary impact that occurs within the impact velocity range modeled in iSALE and velocity fraction range stated above, we interpolate an estimate of the mass of chondrules formed. By summing the mass of chondrules formed in each impact that occurs over time, we generate an estimate of the cumulative mass of chondrules formed by impact jetting during the accretion of giant planet cores in the outer solar system.

Results and Discussion: From initial results of giant planet core formation using LIPAD, we find that the mass of chondrules produced by impact jetting, assuming vertical impacts, ranges from 10^{20} to 10^{22} kg. The lower bound of this range corresponds to impacts between bodies that are 50% ice by mass, and the upper bound corresponds to impacts between pure dunite bodies. Our results indicate that despite the higher overall mass present in the outer solar system, the total mass of chondrules formed there during impact jetting may be comparable to the jetted chondrule mass produced in the inner solar system [1]. This may be consistent with the lower fraction of chondrules observed in many carbonaceous chondrites [4]. The mass of chondrules produced by impacts in the outer solar system is quite sensitive to when the transition to pebble accretion occurs. In this simulation, the rate of chondrule formation drops off around 0.5 Myr when bodies become large enough for efficient pebble accretion to dominate. These large bodies continue to accrete other bodies, but the impact velocities exceed 7 km/s and we cannot currently consider these high velocity impacts in our calculations of chondrule mass. Although our results are preliminary, this work could help to shed light on the dynamics of accretion of the giant planets. In addition, the iSALE simulations of impact jetting were all vertical impacts, while we expect more realistically occurring oblique impacts to produce larger quantities of chondrule material [5] which could increase chondrule abundances by a few times.

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