THE IMPACT ORIGIN OF CHONDRULES. B. C. Johnson[1], D. A. Minton[2], H. J. Melosh[1,2] [1]Department of Physics, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907, United States (johns477@purdue.edu), [2]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, United States.

Introduction: One of the most compelling arguments for the impact origin of chondrules is the high dust concentrations and total pressures required for chondrules to retain their Na and other volatiles [1]. Recent revised chondrule ages indicate that chondrules formed from ~0-3 Myr after calcium aluminum rich inclusions (CAIs), the oldest solids in the solar system [2]. Dating of iron meteorites and modeling of heating caused by the decay of Al-26 indicate that planetesimals larger than ~20 km in diameter were differentiated and molten at the time of chondrule formation [3]. In addition to a metallic core and molten mantle, these planetesimals likely had a primitive chondritic crust [3].

Chondrite meteorites have a significant metal content, but the settling time of metal droplets in a molten planetesimal is on the order of a year. Hence, we argue against the impact-splashing hypothesis [3,4] and suggest that chondrules, if produced by impacts, are the product of shock heating of the undifferentiated crust of early planetesimals. Here we test this hypothesis using detailed hydrocode impact modeling, a monte carlo planetesimal accretion code, and a radiative transfer model. We find jetting during relatively low velocity impacts can produce mm scale chondrules with cooling rates below 1000 K/hr, typical for chondrules [5]. We hypothesize that these chondrules subsequently accrete onto planetesimals forming part of the planetesimals' primitive chondritic crusts [3]. These planetesimals may survive and subsequently populate the main asteroid belt. Crustal striping by so-called hit and run collisions could explain why chondrites dominate the meteorite record [4,5].

Methods: The GAME planetesimal accretion code is a monte carlo code that simulates planetesimal accretion using a particle-in-a-box analytical formalism [6,7] as modeled as a sequence of discrete mergers of planetesimals. For this preliminary study we focus on a small section of the minimum mass solar nebula between 0.9-1.1AU. The planetesimals initially have a Gaussian size distribution centered at 100 km with a standard deviation of 50 km. From GAME we get estimates of the impactor sizes and impact velocities for all impacts occurring on the planetesimal that grows to the largest size.

In this work we use the two dimensional iSALE shock physics code to model planetesimal impacts [8,9,10]. We model planetesimal impacts as a 10 km diameter sphere impacting a flat target. We treat both the impactor and target as completely damaged porous dunite. We use impact velocities ranging from 1-7 km/s by 0.5 km/s. We do not use different sized impactors as our results can be scaled using hydrodynamic similarity. The choice to ignore target curvature is made to reduce the number of required runs. The choice of a vertical impact is made out of necessity as the resolution required to resolve jetting is too computationally expensive in 3D. Inclusion of target curvature and oblique impacts tend to increase the amount of jetted material (probably not by more than an order of magnitude) [11] so that the estimates presented here are actually a lower limit.

Results: The GAME run ends when each remaining body has depleted its feeding zone of mass. In this particular run the largest body remaining has a mass of 3.4×10^{23} kg. During accretion in GAME impactor sizes are on the order of 10-1000 km in diameter. Using the iSALE models we estimate the amount of melted material, in terms of a fraction of a projectile mass, as a function of ejection velocity for each different impact velocity modeled. Using the impact parameters from the GAME run and linearly interpolating between iSALE runs we can estimate the mass of chondrules produced during planetesimal accretion (Figure 1).

As Figure 1 shows no chondrules are produced until ~1 Myr. This is because at impact velocities below ~2.5 km/s either no melted material is produced or ejected at higher than escape velocity. For a typical minimum mass solar nebula at 1 AU, these velocities are not reached until 1 Myr after the GAME run begins with the initial conditions previously described. However we know that chondrules formed as early as CAIs [2]. It is likely that using a more massive solar nebula, larger initial planetesimals, or looking at a region closer to the sun where orbital velocities are higher, would reduce the time from the beginning of the GAME run to the time when velocities exceed 2.5 km/s and chondrules can be produced. However, it is unclear that t=0 in the GAME runs corresponds with t=0 according to CAI's. It is possible the ages of CAI's actually correspond to a time when large planetesimals were already present.

Figure 1 also shows that an increase in porosity leads to a decrease in chondrule production. This is somewhat counterintuitive because porous material melts at lower peak shock pressures. The decrease in chondrule production occurs because an increase in porosity makes jetting less efficient. However increasing the porosity from 1% - 10% only changes the total chondrule mass by a factor of ~2.

We find that there are 23 chondrule producing impacts occurring on the planetesimal that ultimately ends up being the largest remaining body. Together these impacts create more 10^{21} kg of chondrules. The total mass of chondrules created in the solar system is estimated at ~10^{24} kg [5]. To make a comparison to this total mass we need consider all of the impacts taking place during accretion, not just the impacts onto the body that ends up being the largest remaining.

In our model, chondrules are made in discrete impact events. The mass of chondrules will be dominated by the largest impact events. The higher velocity impacts between larger planetesimals that occur later in time should produce a bias toward younger ages. This result is consistent with observations that most chondrules are younger, with ages of ~1.5-2.5 Myr after CAI [3]. Although large impacts certainly continue to occur later than 3 Myr after CAI, gas in the solar nebula is expected to clear out around this time [2]. A gas density of at least 10^{-12} kg/m^3 is required to damp down the relative velocities of chondrule in 1 orbit at 1AU. Without this gas present chondrules will have high relative velocities and break up as they collide with other objects. Higher gas densities are required if chondrules are accreting onto bodies with significant escape velocities.

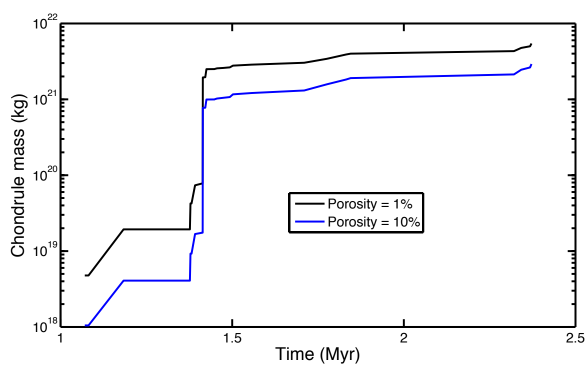

Figure 1: Cumulative mass of Chondrules created by impacts on the planetesimal which ultimately ends up being the largest remaining body in the GAME simulation. Any partially melted material ejected at higher than escape velocity is assumed to produce chondrules. Partially melted material is any material that releases to a temperature above 1373K, the solidus of dunite.

Figure 2 shows estimates of the size of melt-droplets produced by jetting. Figure 2 is produced assuming that estimates of the size of melt droplets produced in the ejecta curtain, as a function of impact velocity, ejection velocity, and impactor size apply to jetted material [12]. For impactor sizes of 10-1000 km in diameter the jetted droplets are mm in scale for a range of impact velocities. This size is consistent with observation of chondrules [5].

Another important constraint of chondrules are the 10-1000 K/hr cooling rates implied by the igneous textures that chondrules exhibit [5]. Our simple 1-D radiative transfer model, of a spherically expanding plume of chondrules, gives cooling rates of 10-1000 K/hr for plume masses between 10^{14} – 10^{19} kg, respectively. Based on geometry, we expect the cooling rates of material ejected as a jet to be higher than material ejected as a spherical plume. We find a minimum jetted mass of ~10^{18} kg and argue that it is plausible that the cooling rates of these large plumes of jetted chondrules will be below 1000 K/hr. However, without radiative transfer models which have the correct geometry of a jet, we cannot yet make a true quantitative estimate of the cooling rates for impact produced chondrules.

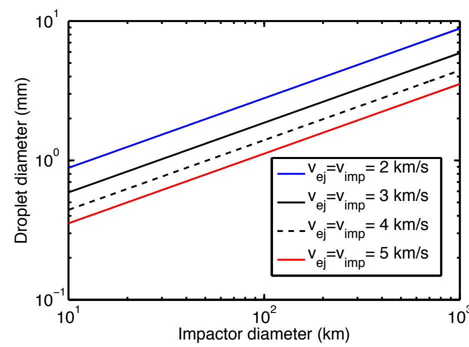

Figure 2: The diameter of droplets ejected with velocities equal to the impact velocity produced by different sized impactors. The jetted material ejected with velocities above the impact velocity will create smaller droplets than these lines show.

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