A PHYSICAL MODEL FOR SIMULTANEOUS PRODUCTION OF CH AND CB CHONDRULES DURING AN IMPACT EVENT.
C. A. Dwyer, F. Nimmo, E. Asphaug, *Dept. Earth & Planetary Sciences, U.C. Santa Cruz, Santa Cruz, CA 95064 (cadwyer@ucsc.edu).*

Introduction. The origin of chondrules is a long-lived conundrum, especially for unusual chondrite groups such as the CH and CB groups. These chondrites are very metal-rich (CH and CB), have much smaller chondrules than average (CH), and have a young formation age (CB chondrules and CB metals). CH chondrites are composed of 70 vol% chondrules, 20 vol% metal, 5 vol% matrix, and trace CAIs [1]. They have an average chondrule diameter of 20 μm, which has led to the proposal that they are vapor condensates from an impact event [2]. However, other work indicates that there might be multiple generations of chondrules within the CH chondrites (e.g., [3]), in which case, our work here applies to one generation, with other generations pre-dating and/or post-dating it.

The CB chondrules have previously been proposed to be produced during an impact event at 4.563 Ga (e.g., [4]). CB chondrites are composed of chondrules (20–40 vol%) and metal (60–80 vol%) and are further subdivided into the $\mathrm{CB_a}$ and $\mathrm{CB_b}$ subgroups, which have average chondrule diameters of 1 cm and 1 mm respectively [1]. The CB metal condensates have a similar formation age [5] to CB chondrules, suggesting a genetic link [4].

It has been proposed (e.g., [6]) that the Isheyevo meteorite is a genetic link between the CH and CB chondrites. A joint impact origin for at least some of the Isheyevo and CH chondrules has been proposed [7].

Proposed Model. We created a physical, analytical model of the vapor spherules and melt droplets produced in an impact as a function of impactor size and velocity. We assume that the target and impactor are initially both completely solid (in contrast with the partially or totally molten planetesimals of [8]) and we require a sufficiently energetic impact to produce vapor. We posit that the CH chondrules condensed from the vapor plume and the CB chondrules come from melt which has experienced aerodynamic modification from the vapor plume. The age of CB chondrules puts this event during solar system formation.

In this work, we refer to material which cooled from melt to be 'melt droplets' and material which condensed from the vapor phase to be 'vapor spherules.' Both droplets and spherules are assumed to be chondrules.

Method. The formula for the average melt droplet is equation 8 of [9]:

$$d_m = aD_{imp}^{1/2}v_{imp}^{-1} \qquad (1)$$

where $a = 0.22 \ \mathrm{m^{3/2}/s}$, d_m is the diameter of the melt droplet, D_{imp} is the diameter of the impactor and v_{imp} is the impact velocity. This derivation assumes that the parent melt drop breaks up due to interaction with the vapor and that the subsequent melt droplet size is determined by a balance of aerodynamic force and surface tension. The impactor and target are assumed to be composed of the same material. Thermodynamic data of quartz are used and surface tension is assumed to have a constant value of 0.3 N/m. At the level of precision of this work and over the parameter range of interest, there is no difference between this model and a model assuming that the melt droplets formed without aerodynamic modification from a vapor plume (equation 1 of [9]).

The formula for the average size of a vapor spherule is based on data from [10]. Their data come from simulations using a 1-D Lagrangian hydrocode with an ANEOS equation of state for SiO_2 (including a temperature-dependent formulation for surface tension), nucleation (including kinetic frustration) of spherules, and growth of spherules. They assume that the vaporized material is entirely and only the isobaric core. They model the impactor and target as composed of the same material. The two competing processes which control the diameter of a vapor spherule as a function of v_{imp} are surface tension and expansion rate. At low velocities, the effect of surface tension dominates (an increase in v_{imp} causes a decrease in the temperature of nucleation which causes an increase in surface tension which results in larger spherules). At higher velocities, the effect of expansion rate dominates (an increase in v_{imp} causes an increase in the expansion rate which results in smaller spherules).

Since the dominant physical processes are different at low and high velocities, we apply two independent fits: one to the low velocity region (where spherule size is controlled by surface tension) and one to the high velocity region (where spherule size is controlled by expansion rate). This clear separation into physical regimes gives us more accurate results and better fits. Specifically, we fit spherule radius normalized to impactor diameter as a function of impact velocity, with $D_{imp} \in \{1 \text{ km}, 10 \text{ km}, 10^2 \text{ km}, 10^3 \text{ km}, 10^4 \text{ km}\}$. The low velocity solution was fitted over $v_{imp} \in$ [15 km/s, 20 km/s] and the high velocity solution was fitted over $v_{imp} \in$ [36 km/s, 50 km/s]. The fits have the form:

$$d_v = bD_{imp}\mathrm{e}^{v_{imp}/c} \qquad (2)$$

where d_v is the diameter of a vapor spherule. For the low velocity fit, $b = 2.29 \times 10^{-16}$ and $c = 1.112$ km/s and for the high velocity fit, $b = 1.18 \times 10^{-4}$ and $c = -3.919$ km/s.

If d_m and d_v are known, eq 1 and eq 2 can be solved simultaneously for v_{imp} and D_{imp}. Note that both the vapor and melt equations give the average spherule or droplet diameter produced by their respective method. The impact will produce spherules and droplets which are not average. In order to determine the appropriate values of d_v and d_m to use in our calculations, we assume that the meteorite collection on Earth contains chondrules representative of those produced in the impact. For d_v, we use 20 μm, the average diameter of the CH chondrules. Due to the variety shown in the CB group, we use the range [1 mm, 1 cm] for d_m. The endpoints of this range are the average diameters of the CB_b and CB_a subgroups respectively.

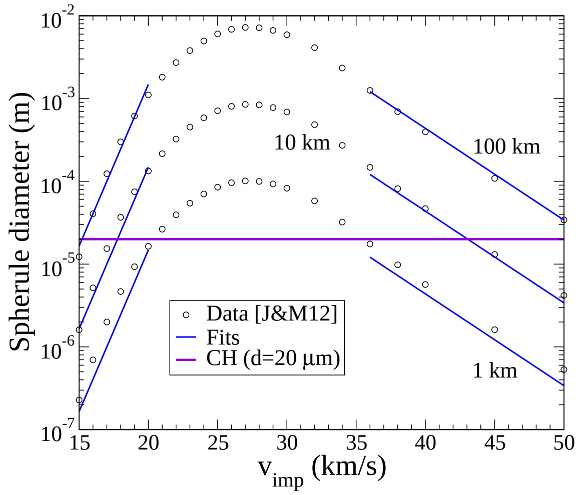

Figure 1: The vaporization model points for $D_{imp} \in$ [1 km, 10 km, 100 km] of [10] (open circles labeled with D_{imp}), our fit (eq 2) for the same D_{imp} (solid blue line), and the average diameter of the CH chondrules (horizontal purple line). Any $(D_{imp},\ v_{imp})$ pair which lies on the CH line satisfies the constraint provided by the average CH chondrule diameter.

Results. The intersection of the vapor spherule fit with the CH chondrule diameter is shown in Fig 1. The constraints from using both CH and CB chondrules are shown in Fig 2, which shows the two possible sets of solutions solutions. The low velocity solution occurs over the range between $\{d_m = 1\text{ mm},\ v_{imp} = 18\text{ km/s},\ D_{imp} = 7\text{ km}\}$ and $\{d_m = 1\text{ cm},\ v_{imp} \approx 14\text{ km/s},\ D_{imp} \approx 400\text{ km}\}$. The high velocity solution occurs over the range between $\{d_m = 1\text{ mm},\ v_{imp} = 49\text{ km/s},\ D_{imp} = 50\text{ km}\}$ and $\{d_m = 1\text{ cm},\ v_{imp} \approx 70\text{ km/s},\ D_{imp} \approx 10,000\text{ km}\}$.

Discussion. Fig 2 gives two scenarios for simultaneous generation of CH and CB chondrules: low velocity collisions ($v_{imp} \leq 18$ km/s) with moderate-sized impactors ($D_{imp} \in [7\text{ km},\ 400\text{ km}]$) or high velocity collisions ($v_{imp} \geq 49$ km/s) with large impactors ($D_{imp} \geq 50$ km). Collisions with velocities $\geq$50 km/s are likely to be rare, except at semi-major axes interior to 1 AU. This might explain why the meteorite collection has such a sparse record of droplets and spherules produced by impacts. Collisions with velocities appropriate to the low velocity region ($v_{imp} \sim 16$ km/s) occurred much more frequently than for the high velocity region but at such low velocities it may be difficult to generate sufficient volumes of vapor. However, if the impactor or target is initially partially molten, vaporization would occur at lower v_{imp}.

The diameter of the target is not defined in our model apart from the trivial requirement that it be at least as large as the impactor. In general, v_{imp} tends to scale with escape velocity, which is dependent upon the mass of the body, so a higher v_{imp} is more likely to occur for a larger target body, but that is by no means an absolute. A larger target might facilitate accumulation of ejecta material into a geologic unit, which could aid preservation. We note that a full analysis of the statistics of occurrence and preservation is beyond the scope of this paper.

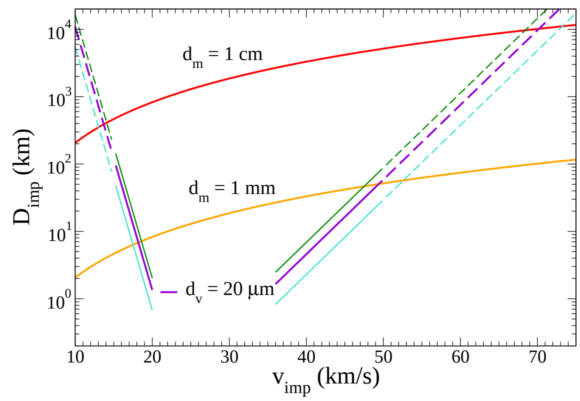

Figure 2: Simultaneously solving for production of CH (d_v) and CB (d_m) chondrules (eqs 2 and 1 respectively). Both d_m lines are labeled whilst only the middle d_v line is labeled for the sake of clarity. The upper and lower d_v lines correspond to diameters of 30 μm and 10 μm respectively. The d_v lines are dashed where they are extended beyond the range of data used in the fit. An impact which can simultaneously produce vapor spherules and melt droplets is indicated by an intersection of d_v and d_m lines.

Our model assumes that both the target and impactor are individually homogeneous in composition, have the same composition, and that the thermodynamic properties of that composition are well-approximated by SiO_2. These approximations were made for ease of computation and due to the available experimental data. However, although the CH and CB chondrules are silicate, chondrites from both groups contain significant amounts of Fe-Ni metal, and CB chondrules and metal have similar ages [4][5], which suggests co-formation of CB chondrules and metals. Thus a full understanding of the impact event must include metal as well as silicate phases. The silicate/metal heterogeneity seen in CH and CB chondrites could have been achieved via a radially heterogeneous impactor (i.e., partially or fully differentiated) and/or lateral compositional heterogeneities in the impactor and/or target. Impact simulations are needed to investigate the origin of the silicate/metal heterogeneity as well as the chondrule/metal ratios of CB_a, CB_b, CH, and Isheyevo chondrites. Impact simulations would also allow calculation of such things as the size distribution of melt droplets and vapor spherules, which could then be compared with the meteorite collection.

Acknowledgements. C.A.D. thanks J. N. Cuzzi for insightful discussions and J. V. Wasem for advice on fits.

References. [1] Weisberg, M.K. et al., in: MESSII, UAz Press, 19–52, 2006. [2] Wasson, J. & Kallemeyn, G., EPSL 101, 148–161, 1990. [3] Krot, A.N. et al., LPSC, #1224, 2006. [4] Krot, A.N. et al., Nature 436, 989–992, 2005. [5] Kleine, T. et al., GCA 69, 5805–5818, 2005. [6] Ivanova, M.A. et al., LPSC, #1100, 2006. [7] Krot, A.N. et al., MAPS 44, A116, 2009. [8] Asphaug, E. et al., EPSL 308, 369–379, 2011. [9] Melosh, H.J. & Vickery, A.M., Nature 350, 494–497, 1991. [10] Johnson, B.C. & Melosh, H.J., Icarus 217, 416–430, 2012.