SIZE DISTRIBUTION OF CHONDRULES SET BY DROPLET BREAKUP AND COUPLING DURING VAPORIZING COLLISIONS IN THE NEBULA. S. J. Lock[1], S. T. Stewart[2], P. J. Carter[2], E. J. Davies[2], M. I. Petaev[3] & S. B. Jacobsen[3], [1]Caltech (slock@caltech.edu); [2]University of California Davis; [3]Harvard University

Introduction: Chondrites are primitive meteorites containing silicate spherules, known as chondrules, embedded in a fine-grained matrix. Chondrules have a narrow size distribution with radii on the order of 0.1 to 1 mm [1, 2]. Chondrules were transiently molten droplets, and their characteristic size is a strong constraint on models of chondrule and chondrite formation.

At this meeting, Stewart et al. [3] propose that vaporizing collisions between planetesimals in the presence of the solar nebula instigate the formation of chondrules and chondrites. During decompression from the impact shock, vaporizing material expands in volume by many orders of magnitude and drives a bow shock into the nebula. Driven by the momentum of the outward flow, the plume expands to lower pressures than the surrounding nebula. The low-pressure plume is an unstable feature, and secondary waves develop to reverse the flow direction and hydrodynamically collapse the plume [4]. Condensed material, derived from both the planetesimals and free-floating nebular debris, is concentrated by coupling to the converging flow during plume collapse, which forms a cloud of warm gas laden with condensates. The potential to form new planetesimals from the concentrated material is discussed in [5].

In a vaporizing event, a portion of the colliding bodies is melted. In addition, some regions of the bow shock are hot enough to melt nebular dust. Here, we investigate the size distribution of melt fragments in the vapor plume. We show that shearing flows during expansion and collapse break up droplets and impose a maximum size (0.1-1 mm) determined primarily by the density of the nebula. We also propose that, due to the longer coupling timescales for large particles, any particles larger than ~1 cm are not concentrated during collapse, explaining the absence of larger fragments in chondrites.

The critical size of chondrules in a shearing flow [e.g., 6-8] and coupling to the nebula [e.g., 9] have been considered previously in the context of other chondrule formation mechanisms. We build on this work and apply these concepts to the collapsing vapor plume model.

Methods: The maximum stable size of droplets in a shearing flow can be approximated by equating the force required to overcome the surface tension of a droplet with the drag force exerted by the vapor,

$$F_{drag} = \frac{1}{2} C_D r_{max}^2 \rho_{vap} (\Delta v)^2 = F_{\hat{\gamma}} \sim 2\pi\hat{\gamma} r \ ,$$

where C_D is the drag coefficient, r_{max} is the maximum stable droplet radius, ρ_{vap} is the vapor density, Δv is the differential velocity between the droplet and vapor, and $\hat{\gamma}$ is the droplet surface tension. We calculate the maximum droplet size of silicates with a surface tension given by [10] in an ideal 0.818 H_2 to He mixture at 2000 K. The results are very similar for water vapor. The form of the drag coefficient depends on the size of the droplet relative to the mean-free path of molecules in the gas, L_{MFP}. When $r \gg L_{MFP}$, the drag is controlled by the dynamic viscosity of the vapor. We refer to this regime as the viscous regime and use the prescription

$$C_D^{visc} \cong \left[\left(\frac{24}{Re} + \frac{40}{10 + Re} \right)^{-1} + 0.23Ma \right]^{-1} + \frac{(2-w)Ma}{1.6 + Ma} + w$$

where $Re = 2r\rho_{vap}\Delta v/\mu$ is the Reynolds number, μ is the dynamic viscosity of the vapor, $Ma = \Delta v/c_s$ is the Mach number, c_s is the sound speed in the vapor, and w is 0.4 if $Re < 2{\times}10^5$ and 0.2 if $Re \geq 2{\times}10^5$ [11]. The vapor viscosity as a function of temperature was calculated using a power-law fit to literature data [12-14]. When $r \ll L_{MFP}$, droplets do not significantly perturb the velocity distribution of gas molecules. Momentum transfer is mediated by collisions between gas molecules and the droplet, and an Epstein drag prescription is used,

$$C_D^{Ep} = \frac{2}{3\Lambda}\left(\frac{\pi T_{cond}}{T_{vap}}\right)^{\frac{1}{2}} + \frac{2\Lambda^2 + 1}{\sqrt{\pi}\Lambda^3} e^{-\Lambda^2} + \frac{4\Lambda^4 + 2\Lambda^2 - 1}{2\Lambda^4} \mathrm{erf}\,(\Lambda)$$

where

$$\Lambda = \Delta v \sqrt{\frac{m_a}{2k_B T_{vap}}}$$

and T_{cond} and T_{vap} are the temperatures of the condensate and vapor respectively ($T_{vap} = T_{cond}$), m_a is the mean molecular mass of the vapor, and k_B is Boltzmann's constant [15]. The authors are not aware of a satisfactory treatment of the transition between the viscous and Epstein regime, i.e., for when $r \sim L_{MFP}$. Here, we consider the transition between the viscous and Epstein regimes to occur instantaneously when $r = 4L_{MFP}/9$.

We calculated the stopping time, or equivalently coupling time, of droplets by integrating the acceleration due to the drag force assuming that the velocity of the gas and the radius of the droplet were constant.

Droplet breakup: The red line in Fig. 1 shows the maximum stable size of droplets for a given differential velocity. Even in low density gas, roughly equivalent to the ambient nebula (Fig. 1, top), fluid bodies >1 m are unstable when the differential velocity is more than a few 100 m s^{-1}. During acceleration of condensates, there is many orders of magnitude more kinetic energy available than required to create the increased surface area of droplets of the critical size. Liquid fragments in the expanding vapor plume, or incorporated into the bow shock, would be broken down to a range of different sizes depending on the local shear and gas density.

During the initial collapse of the vapor plume, reverse shocks propagate back into the plume. These shocks rapidly reverse the flow leading to a large differential velocity with the condensates as they are dragged inwards. The shear between the liquid and reversing vapor flow is felt by material that is collected by the inward flow. This shear during reversal imposes the maximum size of droplets in the collapsed vapor plume.

At differential velocities above about ~1 km s^{-1}, the critical size of droplets becomes only weakly dependent on the differential velocity and plateaus at a value dictated by the gas density. The density of a strongly shocked gas is a factor of $(\gamma+1)/(\gamma-1)$ (~6) times the pre-shock density, where γ is the ratio of specific heat capacities. Thus, the density of the shocked nebular gas is relatively insensitive to the impact conditions [4]. For such gas densities (e.g., Fig 1., middle panel), the maximum size is 0.1-1 mm, consistent with chondrule sizes. Thus, in the collapsed vapor plume model, we propose that the maximum size of chondrules is set by the global property of the density of the nebula, explaining the similarity in maximum chondrule sizes in different chondrites [1,2].

A range of droplet sizes is expected, below the maximum size, due to heterogeneous shear in the plume.

Coupling of condensates during collapse: The coupling time of condensates is highly sensitive to their size (Fig. 1). The coupling time for silicate droplets larger than ~1 cm are on the order of several hours to days, longer than the time for the dynamical collapse of the plume. During the supersonic collapse, silicates larger than ~1 cm would be left behind by the reversing flow and would not be efficiently concentrated in the collapsed plume. The stopping time of metal particles is several times longer than for silicates, consistent with the smaller size of metal grains in chondrites.

Conclusions: Shear between condensates and vapor in the expansion and collapse of impact-produced vapor plumes in the nebula breaks down large molten fragments into a range of sizes. The characteristic maximum size of chondrules, 0.1-1 mm, is set by the density of the gas during vapor plume collapse, which in turn is determined by the density of the nebula. Collapse of the vapor plume concentrates only small particles. Thus, formation of new planetesimals from material concentrated by a collapsing vapor plume may explain the absence of larger sized fragments in chondrites.

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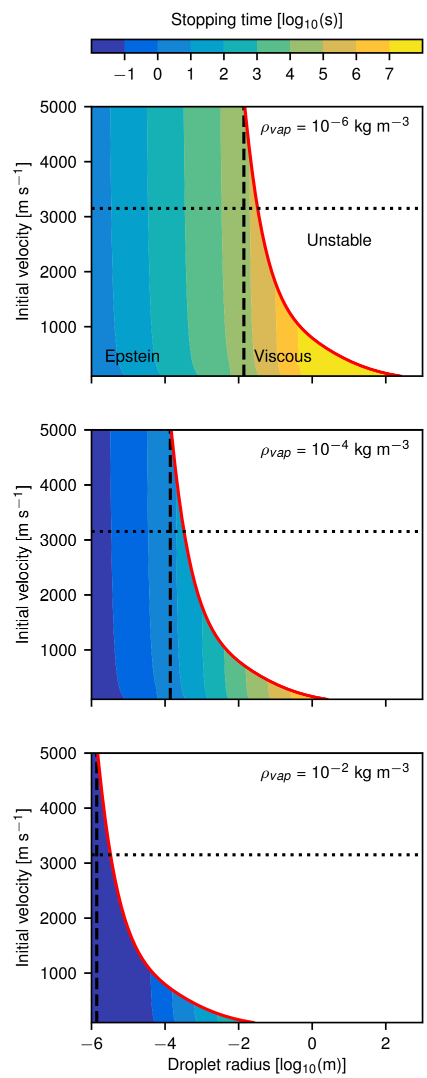

Figure 1: The stopping time for a spherical droplet of a given radius (x-axis) from an initial velocity (y-axis) to 10 m s^{-1}. Red line shows the maximum stable size of spherical droplets. Vertical dashed line shows the transition from the viscous to the Epstein regime. Horizontal dotted line is the sound speed nebula gas at 2000 K. Panels show different gas densities.