THE COLLISIONS OF CHONDRULES BEHIND SHOCK WAVES. F.J. Ciesla[1] and L.L. Hood[2], [1]NASA Ames Research Center; MS 245-3; Moffet Field, CA 94035; ciesla@cosmic.arc.nasa.gov; [2]Lunar and Planetary Laboratory; University of Arizona; 1629 E. University Blvd; Tucson, AZ 85721; lon@lpl.arizona.edu.

Introduction: One of the reasons that the mechanism(s) responsible for the formation of chondrules has remained so elusive is that each proposed mechanism must be able to explain a large number of features observed in chondrules. Most models of chondrule formation focus on matching the expected thermal histories of chondrules: rapid heating followed by cooling during crystallization at rates between ~10-1000 K/hr [1, and references therein]. Thus far, only models for large shock waves in the solar nebula have quantitatively shown that the thermal evolution of millimeter-sized particles in the nebula can match these inferred thermal histories [2-4]. While this is a positive step for the shock wave model, further testing is needed to see if other properties of chondrules can be explained in the context of this model.

One area of interest is understanding the collisional evolution of chondrules after they encounter a shock wave. These collisions could lead to sticking, destruction, or bouncing. Here we focus on understanding what conditions are needed for these different outcomes to occur and try to reconcile the seemingly contradictory conclusions reached by studies of compound chondrule formation and chondrule destruction by collisions behind a shock wave.

Chondrule Collisions: The observation of compound chondrules in meteorites has led to the realization that chondrules were susceptible to collisions while still in their molten state during the formation process [5,6]. The frequency of these objects has been used to put constraints on the density of chondrules in the nebula during a chondrule formation event [3,5,7]. By assuming a relative velocity between the chondrules and a time interval during which the chondrules were likely to "stick" upon experiencing a collision, previous workers have calculated that the ratio of chondrule mass density to gas density would be, on average, 0.15-0.30. These models have typically assumed a value for the relative velocity between the chondrules to be 100 cm/s, which has been constrained by estimates of chondrule surface tension [8]. This is roughly the relative velocity expected in a turbulent nebula with a value of $=10^{-4}$ (dimensionless turbulence parameter).

In the shock wave model, relative velocities between the particles will arise in a different way. As the particles enter the shock, they will be moving with some relative velocity with respect to the gas. It is this relative motion that leads to the heating of the particles and their subsequent deceleration. The force exerted on a particle by the gas will depend on its velocity, temperature, and size. Thus particles of different sizes will decelerate at different rates, leading to relative velocities between the particles.

This effect was studied by Nakamoto and Miura [9] who calculated the rate at which particles of different sizes would collide and the energy associated with those collisions. Assuming that those particles which experienced collisions such that the energy of the colliding particle ($m_2v^2/2$) was greater than the strength of the particle(m_1/f, where $=3x10^6$ erg/g, and f=0.3 is an efficiency factor) was destroyed, these authors explored how likely particles of different sizes were to survive behind a shock wave under various conditions. They concluded that in order to produce the observed chondrule size distribution, the ratio of chondrule mass density to gas mass density should be on the order of or less than 0.01 (close to the average value in a canonical solar nebula). If this ratio was exceeded, the larger chondrules observed in meteorites would not survive.

Thus the results of compound chondrule studies seem to be inconsistent with the survival of chondrules behind a shock wave. In order to produce the observed number of compound chondrules, the particles must have been concentrated at relatively high mass ratios. However, such high mass ratios may not allow those chondrules to survive the formation process. We are currently investigating ways that these contradicting calculations can be reconciled.

Model Development: By calculating the rate at which different particles are decelerated as they flow behind a shock wave, we can calculate the relative velocity between two particles of different sizes. Given the relative velocity between two particles (particle 1 with radius r_1 and particle 2 with radius r_2), we can then calculate what the number density of particles the same sizes as particle 2 would have to be to ensure that a given particle 1 would collide with one of these particles ($n_2=1/ \; r_1^2vt$, where t is the time that the particles are susceptible to collisions and v is the relative velocity). If we limit ourselves to those velocities which would lead to the destruction of particle 1, based on the criteria described above, then we can calculate what the minimum number density would have to be to ensure that particle 1 would be destroyed in these collisions.

Size Distribution of the particles. In general, large relative velocities (large enough to lead to destruction of a particle) can be achieved between the particles considered. However, when particle 2 has a radius which is close in value to that of particle 1, the velocities of the particles do not differ significantly at any point behind the shock wave. This means that the criteria for destruction would not be met—that is that the collisional velocity between the particles would be too small to lead to destruction. Thus, if the particle size distribution entering the shock wave is narrow, then very few particles may be destroyed due to collisions. Models of the redistribution of particles in the solar nebula by turbulence predict that particles of similar size (actually similar products of radius and mass density) are preferentially concentrated by turbulent eddies [10]. Thus this "window" of low relative velocity of the particles may be due to the size selection of turbulence in the nebula. We are investigating the dependence of the size of the window and the size distribution of particles in eddies on nebular parameters.

Results of Collisions. In the compound chondrule investigations described above, the velocity of the collisions was thought to be on the order of 100 cm/s or less, because surface tension arguments suggest that larger collisional velocities would disrupt the chondrules [8]. However, this velocity is much less than the disruption velocities for particles using the criteria outlined in [9]. While slight differences in the critical velocity for disruption can be expected due to large uncertainties, differences of several orders of magnitude will lead to the discrepancies described above. This must be examined more closely.

In [7], we outlined a simple model to describe the conditions needed for two viscous particles to stick based on Hertzian contact theory of two spherical particles. Specifically, the collisional time between two spherical particles must be less than the Maxwell time. The Maxwell time is a property of a given material: on timescales short compared to the Maxwell time, the material will behave elastically and collisions will lead to bouncing or disruption; on timescales long compared to the Maxwell time, the material will behave viscously and collisions will lead to flow or sticking of the chondrules. This model can be expanded to consider the variability of the Maxwell time with impact parameters as well as composition and temperature variations in the behavior of the chondrules. A more complex model will help to constrain what will happen when two chondrules collide at a given velocity.

Compound Chondrule Formation at High Velocities. Should large velocity collisions allow for the formation of compound chondrules, we can estimate the formation rate of compounds based on the relative velocities calculated above. In addition, we can improve upon previous compound chondrule calculations by considering particles of various sizes. In their investigation of compounds, Wasson et al. [6] detailed the various sizes of the different components of compound chondrules and showed that the primaries and secondaries may have very different sizes from one another. While these observations may be the result of uncertainties due to observing the compounds in thin-section [7], they may also be the result of the way the objects formed.

Summary: The collision of two chondrules can lead to a number of outcomes: the chondrules may stick and form a compound chondrule, one or both of the chondrules may be destroyed, or the two chondrules may simply bounce off of one another. Behind a shock wave the relative velocity between two chondrules may vary over many orders of magnitude. Understanding the conditions needed for each of these outcomes to be satisfied is important in evaluating if chondrules could have been formed by shock waves in the solar nebula.

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