ACCRETION AND HEATING OF PARTICLES BY SUPERSONIC PLANETESIMALS. F. J. Ciesla, *NASA Ames, Moffet Field, CA , 94035 (fciesla@lpl.arizona.edu)*, L. L. Hood, *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721*.

Introduction: Recently, nebular shock waves have become one of the leading candidates for explaining the presence of chondrules in primitive meteorites [1-3]. While shocks have been shown to be capable of explaining many of the features of chondrules, a major problem with the theory is that the source of the shocks remains unidentified. Among the suggested sources of the shocks are bow shocks created by supersonic planetesimals in the nebula [4,5].

Recently, we studied the structure of the shocks that would form around such supersonic planetesimals [6]. We found that particles that encountered the shocks at distances greater than 2 planetesimal radii from the planetesimal would cool too quickly to form the textures observed in chondrules. While the region of the shock far away from the planetesimal may not allow chondrules to form, the region closer in has not been studied in detail. In this work we consider the dynamical and thermal evolution of particles that encounter supersonic planetesimals in this region.

Shock Structure: We have simulated the flow of gas around a spherical planetesimal by using the VH-1 code which solves the gas dynamic equations using the piecewise parabolic method (PPM). In particular, we consider planetesimals 10 km, 100 km, and 1000 km in radius moving at various speeds (4-8 km/s) through nebular gas at a density of 10^{-9} g/cm^3 and a temperature of 400 K (this corresponds to a planetesimal moving at Mach $\sim$3-6). These are typical parameters used and velocities found in [5]. An example of one of our runs is shown in Figure 1. In this case, the planetesimal is 1000 km in radius and moving at a velocity of 8 km/s. While other cases considered vary slightly, the general structure of the shock is similar to that shown (with scale changing appropriately for different sized bodies).

The bow shock forms roughly 1 planetesimal radii in front of the planetesimal. Upon passing through the shock, the gas increases in temperature and density, while its velocity parallel to its upstream velocity decreases. In this same region, the velocity perpendicular to its upstream velocity increases to flow around the planetesimal. This change in flow is what determines how the particles flow around (or into) the planetesimal.

Dynamics of Particles: As the velocity and density of the gas change as it flows through the shock front and around the planetesimal, it will exert forces on the particles suspended within it and change their trajectories. How the trajectories of these particles are affected depends on how coupled the particles are to the gas (measured by their stopping time or distance [7]). Those particles with short stopping distances (smaller particles) will be more strongly affected by the changes in the flow of the gas, while those with long stopping distances will pass through the shock without their trajectories changing significantly.

We have studied the behavior of particles 1 mm in diameter (chondrule sized) and smaller that are suspended in the solar nebula in close vicinity to the supersonic planetesimals described above. The particles are assumed to start (t=0) at some position far upstream of the planetesimal such that the gas flow is not disturbed and move with the same velocity as the gas relative to the planetesimal. As time goes on, the motion of the particles are determined by the forces exerted on them. The forces are calculated using the equations given in [8] for the free-molecular flow approximation.

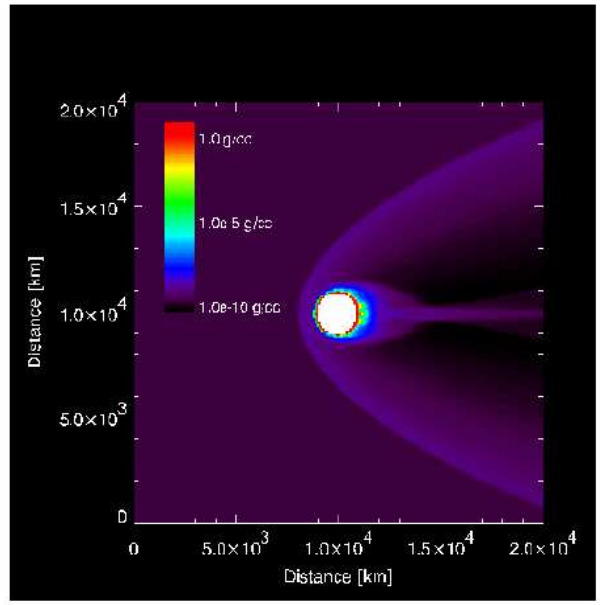

Figure 1: PPM simulation of the bow shock created by a supersonic planetesimal using the parameters described in the abstract.

For planetesimals 10-100 km in radius, we find that chondrule sized particles pass through the shocked gas with little change in their trajectories. Thus, if their impact parameter is less than the radius of the planetesimal, they will be accreted by the planetesimal. However, for the 1000 km planetesimal, the stopping distance of the chondrule sized particles is less than the thickness of the shock and, therefore, the particles are greatly affected by the forces exerted in the transverse direction. Thus, only those particles with very small impact parameters will be accreted, while the rest are swept around the planetesimal.

The same behavior is found for those particles smaller than the chondrules. When the stopping distances of the particles are less than the thickness of the shock (roughly the radius of the planetesimal), the particles are swept around the planetesimal by the gas. When the stopping distance is greater than the shock thickness, then the particles are accreted by the planetesimal.

Thermal History of Particles: In addition to tracking the dynamical evolution of the particles, we have calculated the thermal evolution of the particles as they encounter the planetesimal bow shock. These calculations were also done using the free molecular flow approximation and the equations given in [8]. In general, these equations track the temperature of the particles as they are heated through collisions with the gas and the ambient radiation field, and cool through radiation.

To solve for the temperature of the particles explicitly would require assuming some spatial distribution of particles, knowing their temperatures at every location, and solving the radiative transfer equations in three dimensions. We have not done that here. Instead, we assume that the zone of hot particles is negligible and does not contribute significantly to the background radiation. This is likely a valid assumption for the cases of small shocks (10 km planetesimals) or if the amount of solid material in the shock is low making the shocked region relatively optically thin. Thus, it should be noted that all temperatures reported here are likely an underestimate, but are likely accurate unless the shocks are significantly large or pass through regions of the nebula with very high optical depths.

Only in the cases of 1000 km radius planetesimals were the chondrule sized particles brought to temperatures significantly above 400 K. This again was due to the fact that the stopping distance of the millimeter-sized particles was less than the thickness of the shock. Because of this, the particles could experience significant gas drag heating before being accreted by the planetesimal. In none of the cases considered, however, did the chondrule sized particles reach temperatures between 1700-2100 K which is thought to be necessary in order to form chondrules [9]. Smaller particles reach these temperatures (due to assumed lower emissivities) only for the fastest planetesimals (7-8 km/s). Thus, even if there was significant amount of dust present, the increase in the intensity of the radiation likely would not allow the chondrules to reach these high temperatures.

Discussion: Our current understanding of chondrule formation, while not complete, requires chondrule precursors to be brought to peak temperatures between 1700-2100 K and cool at rates between 10-1000 K/hr [9]. In the modeling that we have done, these peak temperatures can only be achieved by chondrule sized particles if the planetesimal is $\sim$1000 km in radius, moving at 7-8 km/s, and the nebula is locally filled with fine dust with low wavelength averaged emissivities. The dust is required to provide an intense radiation field to aid in heating the chondrules.

In the scenario just described, however, most chondrule sized particles are deflected around the planetesimal by the gas and tend to cool much faster than 1000 K/hr. If the planetesimal were slightly smaller than the 1000 km or not spherical and able to trap some of the chondrules, such that the chondrules are accreted by the planetesimal then this may allow the chondrules to cool more slowly. If they are accreted to the planetesimal, they will be exposed to the radiation field created by the hot particles immediately behind the shock front. The cooling rate would then be determined by the rotation rate of the planetesimal (how quickly it rotates the particles away from the increased radiation field). In this scenario, however, it is unclear whether the chondrules, due to their molten state, would survive the accretional process or be able to accrete fine-grained rims such as those observed in meteorite thin-sections. Thus, while supersonic planetesimals are likely to have existed in the solar nebula, it is unlikely that their resulting bow shocks could have been major chondrule producing mechanisms.

It is possible that heating in bow shocks affected pre-existing chondrules in some way, however. If the chondrules encountered chondrules suspended in the nebula, the chondrules could have been heated before being swept up to the planetesimal. This could have lead to 'hot accretion' where the chondrules are accreted at elevated temperatures. Possible evidence for such processes could be seen in meteorites with highly deformed chondrules, such as that reported by [10]. Support for this would come from lack of matrix or small dust particles in between the chondrules due to those particles being deflected around the planetesimal by the gas.

An interesting result of this work is that large supersonic planetesimals would be inefficient at accreting material while they were orbiting at high speeds (their velocity with respect to the gas would change depending on where the object was in its orbit). Particles less than $\sim$ a few mm would be swept around the planetesimal unless the object was moving slowly with respect to the gas. The location for these low velocities would likely be when the planetesimals were at perihelion and aphelion, which could be at significantly different heliocentric distances depending on the eccentricities. This could mean that the planetesimals were able to accrete material at two different locations in the solar nebula. This could affect the physical and chemical evolution of a planetesimal. Further work is needed.

References: [1] Iida, A. *et al.* (2001) *Icarus* **153** 430-450. [2] Desch, S. and H. Connolly (2002) *Meteorit. Planet. Sci.* **37** 183-207. [3] Ciesla, F. and L. Hood (2002) *Icarus* **158** 281-293. [4] Hood, L. (1998) *Meteorit. Planet. Sci.* **33** 97-107. [5] Weidenschilling, S. *et al.* (1998) *Science* **279** 681-684. [6] Ciesla, F. and L. Hood (2003) *LPSC XXIV*. [7] Weidenschilling, S. (1977) *Mon. Not. R. Astron. Soc.* **180** 57-70. [8] Hood, L. and M. Horanyi (1991) *Icarus* **93** 259-269. [9] Jones, R. *et al.* (2000) in *Protostars and Planets IV* 927-946. [10] Lauretta, D. *et al.* (2002) *65th Met. Soc.*