THE PLANETESIMAL BOW SHOCK MODEL FOR CHONDRULE FORMATION: MORE DETAILED SIMULATIONS IN THE NEAR VICINITY OF THE PLANETESIMAL.

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Introduction: Gas dynamic shock waves in a low-temperature nebula have been considered to be a leading candidate mechanism for providing the repetitive, short-duration heating events that are believed to have been responsible for the formation of chondrules in chondrites [e.g., 1, 2]. It has been found, for example, that shocks with Mach numbers greater than 4 or 5 would be capable of rapidly melting 0.1-1 mm sized silicate particles as required by meteoritic data [3, 4, 5, 6]. Near the nebula midplane where chondrite parent bodies are believed to have formed, possible energy sources for generating multiple shocks include mass concentrations in a gravitationally unstable nebula [7, 8], tidal interactions of proto-Jupiter with the nebula [9, 10], and bow waves upstream of planetesimals scattered gravitationally into eccentric orbits by proto-Jupiter [11, 12, 13]. In a recent study, we have found that chondrule precursors that are melted following passage through a planetesimal bow shock would likely cool at rates that are too rapid to be consistent with meteoritic evidence [13]. However, that study was limited to the bowshock exterior to about 1.5 planetesimal radii (measured perpendicular to the symmetry axis) to avoid complications interior to this distance where large pressure gradients and lateral flow occur as the gas flows around the planetesimal. In this paper, we reconsider the planetesimal bow shock model and report more detailed numerical simulations of chondrule precursor heating, cooling, and dynamical histories in the near vicinity of a representative planetesimal.

Analysis: Figure 1 shows a simulation of gas flow around an irregularly shaped planetesimal using the piecewise parabolic method (PPM) to solve the hydrodynamic equations [14]. In the PPM code, the planetesimal is represented as a high-density, low-pressure fluid with a diameter of ~ 100 km. Although the shock is adiabatic (line emission cooling of the shock-heated gas is neglected), this is a good approximation for the downstream distances considered here (< 1000 km) [15]. The gas is initially assumed to be flowing left-to-right at 6 km/s with a density of ~2 x 10^{-9} gm cm^{-3} and a temperature of 400 K. The gas density distribution resulting from the shock wave is shown in the figure. Immediately upstream of the planetesimal, the shock front forms at a distance of 0.6 to 0.8 planetesimal radii above the surface.

For sufficiently large planetesimals or sufficiently small precursor particles, the shock front stand-off distance will be greater than the stopping distance of formed chondrules moving downstream from the shock front. For example, for the initial parameters given above, the stopping distance of 0.1 mm diameter silicate particles in the shocked gas is about 24 km, significantly less than the shock front altitude.

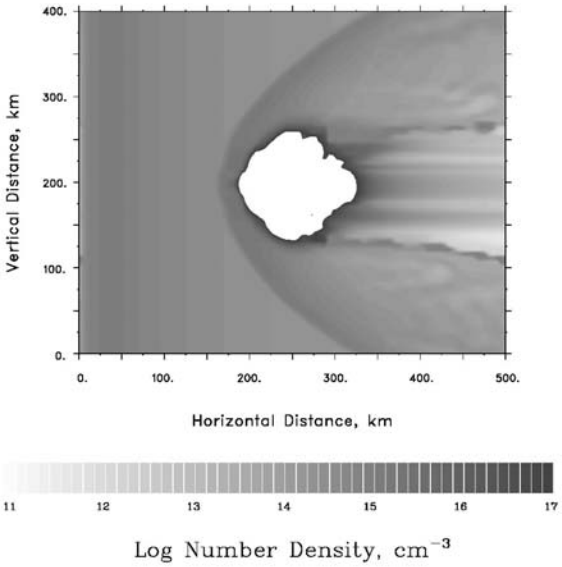

Figure 1. Gas density distribution around a ~100 km diameter planetesimal moving at a speed of 6 km/s relative to the nebula gas (see the text).

To illustrate the dynamical histories of individual particles near the planetesimal, Figure 2 shows the trajectories of 0.1 mm diameter spheres with densities of 2.5 gm cm^{-3} . Particles are initially assumed to be entrained with the gas and moving left to right at 6 km/s relative to the planetesimal. Most particles are deflected around the planetesimal and would likely have cooling rates that are too rapid to be consistent with meteoritic constraints [13] However, a significant fraction of incident 0.1 mm diameter particles impact the planetesimal at very low velocities and are effectively accreted. These particles may have cooling rates substantially lower than than those of the deflected particles because of radiation from the nearby shock front, radiation from surrounding particles and from the planetesimal surface.

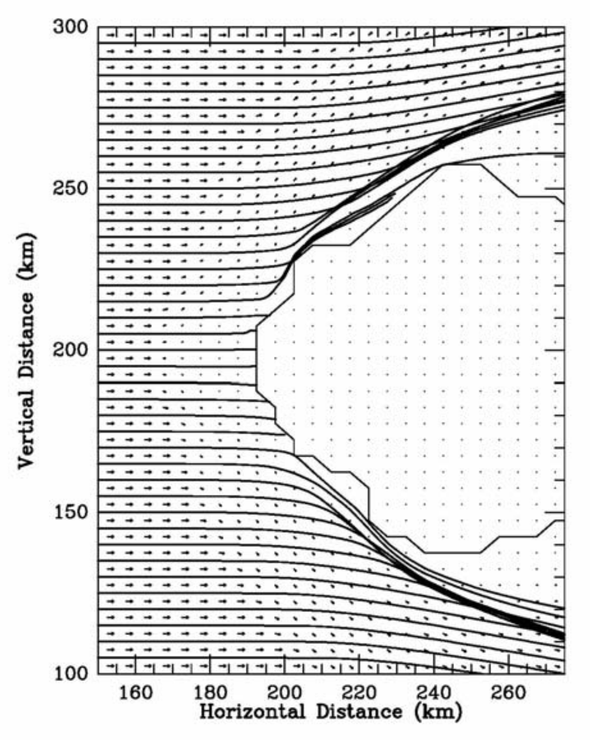

Figure 2. Gas relative velocity vectors (arrows) and trajectories (continuous lines) of 0.1 mm diameter particles entering the bow shock of Figure 1. The location of the planetesimal surface is also outlined.

A simple model to estimate the radius of a planetesimal that would accrete chondrules of a given size following melting in a planetesimal bow shock may be formulated from the condition that the stopping distance of the chondrule in the shocked gas is comparable to the stand-off distance of the bow shock: $d_{stop} \approx 0.6\ R_P$, where R_P is the mean planetesimal radius. For an adiabatic shock in the strong shock limit ($M >> 1$), the mass density of the shocked gas is approximately 6 ρ_0, where ρ_0 is the density of the unshocked nebula gas. Therefore, we obtain for the critical radius,

$$R_P^{crit} \approx (0.6)^{-1} (4/3)\, a\, (\rho_d/6\rho_0)\, (e-1) \qquad (1)$$

where a is the chondrule radius and ρ_d is the chondrule mass density. For example, for $2a = 0.1$ mm and $\rho_0 = 2 \times 10^{-9}$ gm cm^{-3} , $R_P^{crit} \approx 40$ km. This agrees approximately with numerical simulations such as those shown in Figures 1 and 2.

If the size of a parent body for a given ordinary chondrite class is known, it is possible to use equation (1) to estimate the ambient nebula mass density. For example, it has been proposed on the basis of spectroscopic data that asteroid 6 Hebe is a likely source of the H chondrites [16]. Since 6 Hebe has a diameter of 210 km and the mean chondrule diameter for H chondrites is ~ 0.3 mm, it follows from (1) that the ambient gas density was ~ 7×10^{-10} gm cm^{-3} if the H chondrite chondrules formed in planetesimal bow shocks. For a given ambient gas density, parent bodies of different sizes would have accreted formed chondrules with different sizes. For example, if the H and LL parent bodies formed in the same region of the nebula when gas densities were similar, then the LL parent body (mean chondrule size ~ 0.9 mm) should have had a diameter about 3 times larger than that of 6 Hebe according to (1).

A dense boundary layer above the upstream planetesimal surface may exist owing to stagnation of the gas flow and partial vaporization of impacted solids. Such a layer would further decelerate incident particles and would lead to increased solids-to-gas mass ratios that could be consistent with meteoritic evidence. Numerical simulations that consider the existence of this boundary layer are in progress.

Conclusions: For plausible nebula gas densities, strong planetesimal bow shocks will lead to low-velocity impacts (and, therefore, accretion) of formed chondrules with sizes comparable to observed chondrule sizes. If asteroid 6 Hebe is the source of the H chondrites [16] and if chondrules formed in planetesimal bow shocks, then ambient nebula gas densities upstream of the planetesimal were ~ 10^{-9} gm cm^{-3}.

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