EVALUATING PLANETESIMAL BOW SHOCKS AS POSSIBLESITES FOR CHONDRULE FORMATION.

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Introduction: Nebular shock waves are considered among the leading candidates for forming chondrules [1-4] and are also capable of explaining the existence of other components of primitive meteorites [5]. While it has been shown that shock waves can explain the thermal processing of chondrules, the source of the shock waves is still debated. Among the candidates for producing chondrule-forming shock waves are: (1) gravitational instabilities in a massive nebula [6], (2) shocks produced by tidal interactions of the inner nebula with an accreting or migrating Jupiter [7], and (3) supersonic planetesimals in resonance with Jupiter [8,9].

Mechanisms (1) and (2) would likely lead to large scale shocks (10^4-10^5 km in thickness)[6,7], while those shocks produced by supersonic planetesimals would be much smaller [8]. Recent work [3-5] has quantitatively shown that large shock waves can explain the existence of many objects found in primitive meteorites, but similar detailed calculations for smaller shock waves have not been performed. Such investigations are needed now after radiometric dating of chondrules and CAIs [10] has suggested that chondrules formed too late in the nebula to be processed by gravitational instabilities. Thus, while these shocks may have operated in the nebula, they may have been too early to have been responsible for processing chondrules. Therefore, it is necessary to consider those shock waves that would have operated at later stages of nebula evolution. Planetesimal bow shocks would operate in these later stages and may provide a way to account for the difference in ages of CAIs and chondrules [9].

Previous Work: Previous studies have found that planetesimals orbiting in the presence of gas with an already formed Jupiter can be trapped in resonances with the planet [9]. These resonances tended to increase the eccentricities of the planetesimals such that they developed large relative velocities ($\sim$5 km/s or greater) with respect to the nebular gas. Such resonances would occur at distances from the sun in which our current day asteroid belt resides. These velocities would be supersonic and thus the planetesimals would create bow shocks.

Using a two-dimensional piecewise parabolic method (PPM) hydrocode, [8] found that shocks generated in this manner would have thicknesses roughly equal to the diameter of the planetesimal which created them. In addition, it was shown that 25-35 km planetesimals moving at velocities of 5-7 km/s could melt silicate particles on short time scales, consistent with flash heating of chondrules [8]. The cooling rates were not calculated in this work, but it has been suggested that the slow cooling rates inferred for chondrules could be produced if the region where this processing took place was significantly loaded with dust [11].

However, the model in [11] made the assumption that all dust, chondrules, and gas were initially at a uniform temperature and had no relative velocity with respect to one another. If a shock wave passed through a region of the nebula with dust (a=1μm) and chondrules (a=1mm), the shock wave will cause the properties of the gas (temperature, density, velocity) to change across the shock front as predicted by the Rankine-Hugoniot relations. The dust and chondrules will pass through the shock front unaffected, but through collisions of the gas behind the shock front will be decelerated to match the velocity of the gas, while being heated initially through gas drag but then cooled as the relative velocity of the particles with respect to the gas approaches zero. The distance a particle will travel through the gas before its relative velocity disappears (the stopping distance) is equal to the distance through the gas it must travel before encountering a mass of gas equal to itself. This distance is equal to $x_{stop}= \frac{4\rho}{3\rho_g}a$, where ρ is the mass density of the particle and ρ_g is the mass density of the gas.

The mass density of the gas behind a shock wave is typically $\approx 10^{-8}$ g/cm^3, and the mass density of dust and chondrules is $\approx$3 g/cm^3. Using these values, we find that x_{stop} is 200 m and 200 km for the dust and chondrules respectively. Thus, the dust and chondrules will reach equal velocities approximately 200 km behind the shock front. This distance is almost 10 times greater than the thicknesses of the shocks considered by [8]. After the gas passes through the thickness of the shock wave, it returns to its original temperature, density, and velocity [8]. Thus, while the dust will quickly decelerate behind the shock front, it will have reached its peak temperature and start cooling over a very small distance. The chondrules will pass through this hot region of dust, and in fact the whole shocked region, very quickly ($<$10 seconds). At this point, as the gas returns to its pre-shock (cooler) state, the chondrules will be immersed in dust that has already begun to cool, making for a much different situation than that modeled by [11].

If the planetesimals in resonance with Jupiter were larger ($\sim$1000 km), then the shock waves produced would also be larger. In this case, the chondrules would decelerate to the velocity of the gas before the gas returned to its preshock state. Such shocks could still be capable of melting chondrules as described by [8], but it remains to be determined if the cooling rates produced in such shocks would match those inferred for chondrule cooling rates. Chondrules may only be in the shocked region for $\sim$1000 seconds before the gas returns to its original temperature, where they would likely cool rapidly.

Our Model Since the work of [8], detailed models for studying the heating and cooling of silicates behind shock waves in a particle-gas suspension have been developed [3-5]. These models treat each species individually, rather than requiring the quasi-equilibrium state of [11], and therefore would more accurately track their heating and cooling. We have modified the model of [5] to consider the passage of a shock wave of finite thickness (previous studies of shock waves [3-5] have assumed that the shocked zone was an infinite half-space) through a particle-gas suspension. In addition, we replace the ice grains with a=1μm dust grains.

In our model, the nebula is assumed to be at some intial temperature, T_i, with the gas and solids in kinetic and thermal equilibrium far upstream from the shock front. The suspension is heated upstream from the shock front by radiation of hot particles behind the shock. As the shock wave passes through, the gas properties change according to the Rankine-Hugoniot relations. Energy and momentum are exchanged between the gas and solid species, until they pass some distance, x_{shock}, where the gas properties return to what they were immediately before the entering the shock front. This represents the finite thickness of the shock wave. Far behind the shock front, we assume that the suspension returns to its orginal state at a temperature of T_i.

We are currently exploring a large range of parameters with our model, including different shock velocities, initial temperatures, gas densities, particle concentrations, and shock thicknesses, to determine if chondrules can be formed in such a scenario. We define a shock as forming chondrules if the millimeter sized particles reach peak temperatures between 1700 and 2400 K, and have cooling rates between 10 and 1000 K/hr as they approach 1400 K (same criteria used in [5]). We note that cooling rates produced in this model would likely be an underestimate of the actual cooling rates produced by shocks of this type, as this model handles radiative transfer in one dimension. This approximation is fine for the case of large shocks, as the size of the shocked region in the directions perpendicular to the direction the shock propagates will be large compared to the distances over which the chondrules are heated. However, this would not be the case for planetesimal bow shocks, and radiation loss to these directions will likely cool the chondrules even more rapidly.

Discussion: This study is currently in a preliminary stage, and only a small piece of parameter space has been explored. For the cases in which solids are suspended at a solar ratio to the gas (density of solids in suspension is 0.005ρ_g, with 75% of the mass in chondrule-sized particles and 25% in dust as in [3]), we have, so far, not been able to produce chondrules. While the chondrules have been heated to temperatures between 1700-2400 K, their cooling rates have been $\sim$10^{5}K/hr, much too rapid to produce the textures observed in chondrules. However, it has been suggested, as discussed above, that chondrules cooled in a region which was concentrated with dust over the solar value [8,11]. Such scenarios must be investigated for if the solids exit the shocked gas at significantly high temperatures and high concentrations, they may have a large amount of thermal energy compared to the gas. If this is the case, the solids could heat the gas to high temperatures before losing too much heat themselves, and cool at a slower rate.

If planetesimal bow shocks are found to be capable of producing thermal histories for silicate particles consistent with those inferred for chondrules, further investigation will still be needed. Particularly, it must be investigated whether formation in such a manner would be efficient enough to produce the large number of chondrules expected to have been formed in the solar nebula and account for the different textures observed. Also, it must be shown that bow shocks can produce conditions which would allow for the proper percentage of compound chondrules to be formed (see [12]).

If planetesimal bow shocks are found to be incapable of producing thermal histories consistent with those inferred for chondrules, they must be ruled out as a possible chondrule forming mechanism. In addition, if the results of [10] do mean that chondrules formed after gravitational instabilities were likely to have existed in the solar nebula, then that mechanism also must be ruled out. That would leave shocks due to tidal interactions of a nearly (or already) formed Jupiter with the inner solar nebula to be investigated as possible candidates for the formation of chondrules.

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