SHOCK HEATING: EFFECTS ON CHONDRITIC MATERIAL. S. J. Desch[1], F. J. Ciesla[2], L. L. Hood[3], and T. Nakamoto[4]. [1]Department of Physics and Astronomy; Arizona State University; Tempe, AZ 85287; Steven.Desch@asu.edu; [2]NASA Ames Research Center; MS 245-3; Moffett Field, CA 94035; ciesla@cosmic.arc.nasa.gov; [3]Lunar and Planetary Laboratory; University of Arizona; 1629 E. University Blvd.; Tucson, AZ 85721; lon@lpl.arizona.edu; [4]Center for Computational Sciences; University of Tsukuba; Tsukuba 305-8577; Japan; nakamoto@rccp.tsukuba.ac.jp.

Introduction: At the 1994 Conference on Chondrules and the Protoplanetary Disk, shock waves were discussed as mechanisms that may have been responsible for forming chondrules, millimeter-sized igneous spheres which are significant components of chondritic meteorites [1, and references therein]. At the time, shock waves were appealing because they were thought to be brief, repetitive events that were quantitatively shown to be able to rapidly heat silicates to the appropriate temperatures for chondrule formation.

Since that meeting, more detailed models for the thermal processing of material in shock waves have been developed [2-4]. These models have tracked the thermal evolution of the silicates for longer periods of time and found that their cooling rates are also consistent with what has been inferred for chondrules. In addition to the thermal histories of these particles, shock waves may be able to explain a number of other features observed in primitive meteorites. Here, we review the recent work that has been done in studying the interaction of solids with shock waves in the solar nebula.

Source of Shocks in the Early Solar System: Shocks are ubiquitous in astrophysics, and many mechanisms have been suggested that could give rise to shocks in the early Solar System. One is bow shocks around planetesimals moving supersonically with respect to the gas [5]. The scale of these shocks would be roughly the size of the planetesimals. Another source is the accretion of material onto the disk [6]. These shocks would be large-scale but probably not process solids more than once. A promising source of shocks is gravitational instabilities within the disk [7]. These would be widespread and repeatable. Unfortunately, disk models are not yet to the point that we can conclusively identify a source of shocks. Analysis of how chondritic material is affected by shocks can help constrain this astrophysical unknown.

Physics of Heating in Shock Waves: A shock front is the supersonically moving discontinuity between cool, low-density, high-velocity gas and hot, high-density, slow-moving gas. As the fast-moving gas passes through the shock front, it is slowed, compressed and heated according to the Rankine-Hugoniot relations. But the motions of any solids in the gas are not initially affected by the shock front. Solids continue to move supersonically through the gas until they collide with roughly their own mass of gas. This supersonic drift velocity heats the solids just as meteoroids are heated as they pass through the atmosphere. In addition, the solids are heated by thermal exchange with the heated, compressed post-shock gas. Solids may also be heated by absorbing the infrared radiation emitted by other solids and gas molecules. Eventually, the solids come into dynamic equilibrium with the gas, and then also come into thermal equilibrium. The gas and solids return to their pre-shock temperatures. The physics of shock wave heating of solids is one in which heating is relatively sudden and short-lived. Experimental petrology has established that chondrules were heated in exacltly this manner, and the shock wave model has gained favor as the mechanism that melted the chondrules.

Chondrule Formation in Shock Waves: As stated above, three separate groups [2-4] have shown that the cooling rates of millimeter-sized particles suspended in nebular gas overrun by a shock wave can be consistent with those rates inferred for chondrules (10-1000 K/hr). Despite this agreement, the models differ slightly in their assumptions and the conclusions as to how particles are able to cool at these rates. The model of Iida et al. [2] assumed that the gas could cool itself effectively by emitting line radiation, infrared photons generated by transitions between the energy states of water and CO molecules. They assumed these photons could escape the shocked region with high efficiency, so the gas tended to cool rapidly. Since the gas does not stay warm for long, solids, which are mainly heated by frictional heating, stay hot only for as long as they are moving supersonically through the gas. The cooling rate of chondrules in such a model is > 100 K/hr. Desch & Connolly [3] and Ciesla & Hood [4], make the opposite assumption, that line photons cannot escape the shocked region before being absorbed by another water or CO molecule. In that case, the gas can stay warm for longer, and the solids are heated by the gas even after they slow to the gas velocity. Because more solids stay hot for longer, solids absorb more infrared radiation from other chondrules. In such models, chondrules tend to cool at rates of 10-100 K/hr, at rates determined by how quickly the solids can travel several optical depths from the shock front.

Clearly line photons will escape the shocked region with some intermediate efficiency, not being perfectly trapped, but not escaping with perfect efficicency either. The resolution of the problem will come with more detailed modeling of the absorption of line photons by water and CO molecules in the gas. Likely inputs to this calculation will include the spatial distribution of water, which is perhaps influenced by the presence of a snow line [8]. Current solutions very likely bracket the real solution.

Cooling rates are not the only attribute of chondrules that may be explained in terms of the shock-wave heating model. One of the most prominent features of chondrules is that they formed through liquid spheres. However, if the ambient gas pressure is not high enough, liquid silicates, which have high vapor pressures, tend to boil, and they could hardly form chondrules. According to Miura et al. [9], the gas pressure in a region behind shocks is so high that the boiling of liquid particles is suppressed. It should be noted that a condition to heat and melt solids and a condition to keep the molten state stable are independent of each other, but the shock-wave heating model can meet these conditions consistently. Another interesting property of chondrules is their sizes. Susa & Nakamoto [10] pointed out that one of the mechanisms to which the chondrule size distribution may be attributed is the disruption of liquid particles in the high velocity gas flow. When the particles are liquid, those particles are exposed by the fast gas flow behind the shock. And the gas flow exerts the ram pressure on the partilces. When the ram pressure is stronger than the surface tension, which tends to keep the liquid particle spherical and is inversely proportional to the radius of the particle, the liquid particle is expected to break down. In the case of the shock-wave heating model, the maximal size of the liquid particle is estimated to be of the order of 1 mm [10], which is consistent with natural chondrules.

Other Shock Wave Studies: While most studies of shock waves in the solar nebula have focused on whether or not they could form chondrules, a variety of additional effects have also been studied. As some of the proposed shock generating mechanisms would operate on large scales, understanding how shock waves may have affected other objects is needed.

Annealing Dust. In addition to melting millimeter-sized particles, [11] showed that smaller particles can be brought to and maintained at elevated temperatures for extended periods of time. This would allow those grains that formed at large heliocentric distances to be annealed into crystalline grains, which are thought to be present in comets. This may also be important for understanding the structure of small grains that were present near the chondrule forming region.

Chemical Reactions. Associated with shock waves are large increases in gas pressure. These pressures may be larger than those expected at a given location in the nebula. In addition, if a volatile substance is present in the nebula in solid form, and at elevated concentrations, that substance may be vaporized and the resultant partial pressure may be at a value many orders of magnitude higher than is expected under canonical solar nebula conditions. Under such situations, the chemistry of the nebula can be affected. The chemical reactions which take place in the nebula will depend on the temperature, pressure, and concentration of the reacting species. Thus, a shock wave may provide a temporary environment in which chemical reactions can take place that would not otherwise have occurred.

This idea was explored in [12] in looking at the formation of fine-grained phyllosilicates in the solar nebula. The formation of these objects was originally thought to be kinetically inhibited in the solar nebula. However, if a shock wave were to occur in a region of the nebula with a significant ice enhancement beyond the snow line [8], then the temperature at which these objects could form would increase due to the increased pressure. This would allow them to form on very short timescales, provided the shocked gas did not dissipate before the reaction was completed.

Discussion: The occurrence of shock waves in the solar nebula may have played a major role in processing the primitive solids suspended in the gas. This processing may be seen in the thermal evolution of the solids, their chemical evolution, and their dynamical evolution. Understanding how these shock waves were created and operated, therefore, needs to be fully explored. Analysis of chondritic material may provide important constraints on the astrophysical sources of shocks in the solar nebula.

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