GAS-GRAIN ENERGY TRANSFER IN SOLAR NEBULA SHOCK WAVES: IMPLICATIONS FOR THE ORIGIN OF CHONDRULES; L. L. Hood, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721; and M. Horanyi, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309.

Meteoritic chondrules provide evidence for the occurrence of rapid transient heating events in the protoplanetary nebula (1,2,3). Astronomical evidence suggests that gas dynamic shock waves are likely to be excited in protostellar accretion disks by processes such as protosolar mass ejections, nonaxisymmetric structures in an evolving disk, and impact on the nebula surface of infalling "clumps" of circumstellar gas (4,5). Previous detailed calculations of gas-grain energy and momentum transfer have supported the possibility that such shock waves could have melted pre-existing chondrule-sized grains (4). The main requirement for grains to reach melting temperatures in shock waves with plausibly low Mach numbers is that grains existed in dust-rich zones (optical depth > 1) where radiative cooling of a given grain can be nearly balanced by radiation from surrounding grains. Localized dust-rich zones also provide a means of explaining the apparent small spatial scale of heating events. For example, the scale size of at least some optically thick dust-rich zones must have been relatively small (< 10 kilometers) to be consistent with petrologic evidence for accretion of hot material onto cold chondrules (6,7). The implied number density of mm-sized grains for these zones would be $> 30\ m^{-3}$. In this paper, we make several improvements of our earlier calculations to (i) include radiation self-consistently in the shock jump conditions; and (ii) include heating of grains due to radiation from the shocked gas. In addition, we estimate the importance of momentum feedback of dust concentrations onto the shocked gas which would tend to reduce the efficiency of gas dynamic heating of grains in the center of the dust cloud.

To account for radiative losses of the shocked nebular gas in one dimension, radiative loss terms were added to the energy conservation equation of the ordinary gas dynamic shock jump conditions (8). Assuming that hydrogen in the nebula can be approximated as a polytropic gas (constant ratio of specific heats), we have used the ideal gas law and polytropic relations for enthalpy in terms of temperature and pressure. The resulting system of equations was solved numerically to calculate post-shock parameters such as temperature, mass density, and relative velocity. As expected, the post-shock temperature is reduced at a given Mach number compared to that calculated from the ordinary gas dynamic relations and is also a function of initial number density. For plausible Mach numbers (< 6), the nebula number density must exceed $\sim 10^{14}\ cm^{-3}$ for post-shock temperatures to reach levels of at least 850 K as needed (see below) to bring grain temperatures up to silicate melting temperatures in dust-rich zones.

Using the calculated post-shock gas physical parameters for a given Mach number, we have numerically integrated the gas-grain energy and momentum transfer equations as in ref. 4. The pre-shock gas number density was chosen as $10^{14}\ cm^{-3}$ and temperature as 500 K. Radiative energy transfer from gas to grain was accounted for by adding an appropriate T^4 term where T is the gas temperature. The grain emissivity was chosen as 0.75 and the grain absorption coefficient was chosen as 0.9 (albedo 0.1). The grain was assumed to be surrounded by an optically thick cloud of other grains with the same temperature as

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the grain of interest. Results show that complete melting of 1 mm radius silicate grains within a time of $\sim$ 1 minute requires Mach numbers of at least 3.5 under these assumed conditions. An example calculation is shown in Figure 1 for a Mach 4 shock (post-shock gas temperature 920 K and relative velocity 5.7 km/s). The solid fraction (SF) is reduced to zero within 15 seconds. In contrast, an isolated grain exposed to a Mach 4 shock wave reaches a maximum temperature of only 1250 K. One significant contributor to the heating is drag heating due to the translational velocity of the shocked gas relative to an individual grain as the shock wave passes. In reality, grains near the center of a dust-rich zone will experience lower gas relative velocities due to interaction of the up-stream gas with other grains. As an approximate way of gauging the significance of this momentum feedback effect on the shocked gas, we have carried out additional calculations with the gas relative velocity set equal to zero. The shocked gas is assumed to diffuse to the interior of the dust cloud so that heating of grains via radiation and molecular collisions can still occur. Results show that somewhat higher minimum Mach numbers of about 4 are required to melt grains. Of course, dust concentrations that are sufficiently dense as to completely shield their interiors from the shocked gas will not be efficiently heated by this mechanism.

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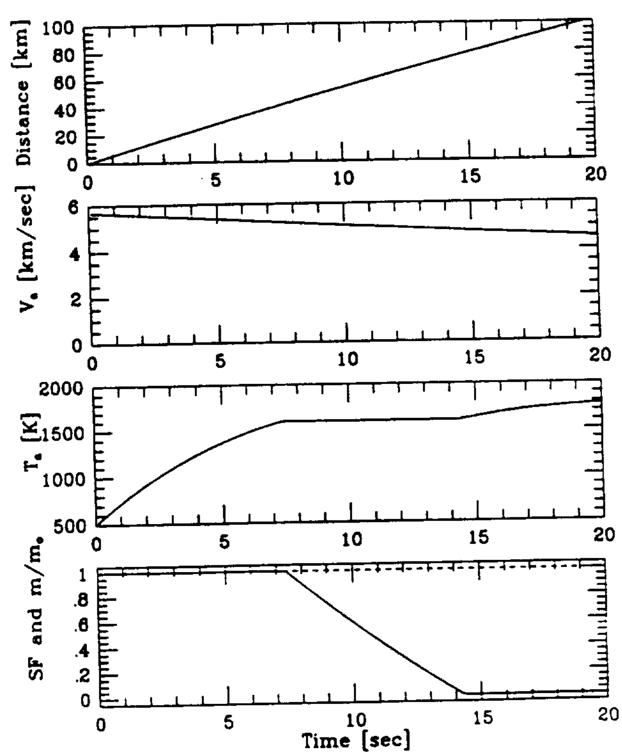

Fig. 1