TYING UP LOOSE ENDS IN CHONDRULE FORMATION BY SHOCKS. **M. A. Morris**[1], **S. J. Desch**[1], and **F. J. Ciesla**[2]. [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287. [2]Department of the Geophysical Sciences, University of Chicago, 5734 Ellis Ave., Chicago IL 60637. (melissa.a.morris@asu.edu).

Chondrule formation is a long-standing problem in meteoritics. Furnace experiments designed to reproduce chondrule textures constrain their cooling rates between their liquidus and solidus temperatures to be in the range 10-1000 K/hr [1]. This constraint, and nearly all other known constraints on chondrule formation, are satisfied if chondrules were melted by passage through solar nebula shocks [2-4]. These models show that after passing through the shock, chondrules are heated by thermal exchange with the shocked gas, by absorption of radiation from dust and other chondrules, and by supersonic drag heating. A standard procedure in such models is to calculate the dynamical and thermal evolution of gas and chondrules separately, under the assumption of a fixed radiation field; once the temperatures of dust and chondrules are known, the emission of radiation can be calculated and the radiation field updated. The solution is then iterated to convergence. While the nebular shock model successfully explains many aspects of chondrule formation, there remain differences between the models [2-4] that predict moderately different physical conditions in the site of chondrule formation, as reviewed by [5]. These differences all involve the calculation of the effects of radiation, especially the radiative losses from molecular line emission, the opacity of solids, and the input radiation field. New quantifications of line emission and initial estimates of its role in chondrule-forming shocks were presented by [6-7] and are not discussed here. In this abstract we discuss the dust opacity and the appropriate jump conditions / input radiation field in chondrule-forming shocks. These last loose ends must be clarified before a complete calculation of chondrule thermal histories in nebular shocks can be carried out.

A major input to calculations of the radiation field (more specifically, the frequency- integrated mean intensity J at all locations) is the input radiation field at the boundaries of the computational domain over which chondrule thermal histories are investigated. Far from the shock front, in the pre-shock region, the radiation field is set to a blackbody radiation field at the ambient temperature $T_{\rm pre}$ of the gas; but it is not clear what the temperature $T_{\rm post}$ in the post-shock region should approach. Both [2] and [4] set $T_{\rm post} = T_{\rm pre}$, while [3] used the jump conditions of [8] to derive a much higher post-shock temperature ($T_{\rm pre} \approx 1100\,{\rm K}$ typically). The isothermal assumption $T_{\rm post} = T_{\rm pre}$ violates the assumption of 1-D, but the jump conditions used by [3] and [8] were incorrect. Below we derive the proper jump conditions, but then discuss why the isothermal assumption is probably best after all.

Jump conditions relate physical conditions (e.g., density ρ, pressure P, temperature T, velocity V) at a point before the shock (1) to those after the shock (2) [see 9]. Immediately before and after the shock (i.e., a few meters), the jump conditions are those of an "adiabatic" shock because insignificant energy is radiated in that interval. The compression of the gas is then $\rho_2/\rho_1 = \eta_{\rm AD}^{-1}$, where

$$\eta_{\rm AD} = \frac{2\gamma}{\gamma+1}\,\frac{1}{\gamma {\rm M}^2} + \frac{\gamma-1}{\gamma+1}$$

where γ is the ratio of specific heats of the gas (adiabatic index) and M is the Mach number [9]. We have included radiative fluxes and the effects of solids (chondrules) in the equations of mass, momentum and energy conservation and have derived new jump conditions appropriate far from the shock. Defining the ratio of chondrule heat energy to gas pressure as $\delta = (\rho_{\rm c,1} c_{\rm P} T_1/P_1)$, we define a new effective adiabatic index $\gamma' = [\gamma + \delta(\gamma-1)]/[1+\delta(\gamma-1)]$. We also define a ratio of net outward radiative fluxes to kinetic energy flux,

$$\epsilon = \frac{\gamma'-1}{\gamma'+1}\,\frac{F_2 - F_1}{\rho_1 V_1^3/2}.$$

Here F_2 (F_1) is the radiative flux in the post-shock (pre-shock) gas. If radiation carries energy away from the shock front, the signs of F_2 and F_1 guarantee $\epsilon > 0$. (The neglect of the sign of the radiative fluxes is one of the flaws of the jump conditions used by [3] and [5]) In terms of these quantities, the new compression is $\rho_2/\rho_1 = \eta^{-1}$, where η solves the quadratic equation $(1-\eta)\,(\eta_{\rm AD}-\eta) = \epsilon$. The post-shock temperature is then easily found:

$$T_{\rm post} = T_{\rm pre}\,\eta\,[1 + \gamma {\rm M}^2(1-\eta)].$$

In an adiabatic shock with no radiative losses, $\epsilon = 0$ and $\eta = \eta_{\rm AD}$, but as radiative losses increase,

ϵ increases, η decreases, and the compression η^{-1} increases. When ϵ is such that $\eta^{-1} = \gamma \mathrm{M}^2$, the solution is the familiar "isothermal" shock.

The above solution for a shocked radiating flow is discussed in the gas-only case by [9], assuming there is no input radiation. This guarantees that $F_2 > 0$ and $F_1 < 0$ so $\epsilon > 0$. We are not aware of solutions for shocked radiating flows that include input radiation. To include input radiation, it would seem appropriate to alter the flux F_2 by an amount $-\sigma T_{\rm post}^4$, so that the post-shock gas can radiative back into the computational domain. Unfortunately, this "reflecting" boundary condition typically drives ϵ to negative values, and is often incompatible with a shock. It is therefore *not* appropriate to set the input radiation field to a blackbody at $T_{\rm post}$ with $T_{\rm post}$ calculated in the purely 1D approximation. Violation of the 1D approximation, at some level, may be necessary for maintenance of a shock in a radiating flow.

One easily understood violation of the 1D approximation involves radiative diffusion carrying energy away parallel to the shock front (for example, out the tops and bottoms of a disk in which the shock propagation direction lies in the plane of the disk). The radiation generated by a nebular shock with lateral extent L will diffuse on a timescale

$$t_{\rm rd} = \frac{3 \rho C_{\rm V} L^2}{64 \pi^2 \, \lambda \, \sigma T^3}$$

[9], where λ the mean free path of photons. For our preferred dust opacity (see below), a post-shock density $\rho = 6 \times 10^{-9}\,{\rm g\,cm^{-3}}$ and temperature 2000 K, $t_{\rm rd} = 2 \times 10^9\,(L/H)^2\,{\rm s}$, where $H \approx 0.2\,{\rm AU}$ is the scale height of the disk. For opacity due to a solar composition of $300\,\mu{\rm m}$ chondrules, $t_{\rm rd}$ is lowered by a factor of 200. These are to be compared to the time for gas and chondrules to reach the computational boundary in simulations, typically $(3 \times 10^5\,{\rm km})/(1\,{\rm km\,s^{-1}}) \approx 3 \times 10^5\,{\rm s}$. If dust evaporates and $L < 0.1H$, then gas will definitely cool to the ambient temperature by the time the post-shock boundary is reached. Other cases are not so clear cut.

The question of opacity is also complicated. Only the opacity due to chondrules was considered by [4], [2] and [10]. In contrast, [3] considered opacity due to both chondrules and a gray (no frequency or temperature dependence) opacity of micron-sized dust, $\kappa = 1.14\,{\rm cm^2\,g^{-1}}$, up to a dust evaporation temperature $T_{\rm evap} = 2000\,{\rm K}$, above which the opacity vanished. For meteoritic abundances of micron-sized dust and chondrules, dust opacity dominates over chondrules, so it is important to include dust opacity, especially as such opacity will be important in shutting off cooling by line emission [6-7]. Dust grains will also typically evaporate, though. The change in specific kinetic energy $(V^2/2)$ exceeds the latent heat of evaporation ($l_{\rm evap} \sim 10^{11}\,{\rm erg\,g^{-1}}$ for chondrule-melting shock speeds ($\sim 7\,{\rm km\,s^{-1}}$). Unlike chondrules, which take minutes to slow (during which time they can radiate), micron-sized dust grains slow in milliseconds and are very poor radiators (being smaller than the wavelength of maximum emission). Thus most of their kinetic energy is converted into heat and they evaporate in milliseconds. So it is appropriate to assume dust grains instantaneously evaporate (as in [3]); however, the evaporation temperature of olivine dust should be taken as 1400 K, not 2000 K.

We are currently implementing these changes into a numerical code to calculate chondrule formation in nebular shocks. A strictly 1D model predicts final temperatures (and therefore input radiation fields) that are not always compatible with shocks. Violations of the 1D assumption are guaranteed on sufficiently large scales; it is beyond the scope of chondrule formation models to calculate the scales on which the gas returns to the ambient temperature. Nonetheless, we will assume in future work that $T_{\rm post} = T_{\rm pre}$. We will include dust opacity by using a temperature-dependent frequency-averaged opacity, and allowing for evaporation of olivine dust at 1400 K (with a small portion of more refractory dust surviving). Chondrule opacity will continue to be included. The effects of chondrule and dust opacity on the shutting off of line cooling will be included according to the formulism of [7]. At this conference, we will present our latest results on chondrule thermal histories incorporating these changes.

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