THE EFFECT OF LINE COOLING IN CHONDRULE-FORMING SHOCKS. **S. J. Desch**[1], **F. J. Ciesla**[2], and **M. A. Morris**[1]. [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287. [2]Department of Terrestrial Magnetism, 5257 Broad Branch Rd. NW, Washington DC 20015. (steve.desch@asu.edu).

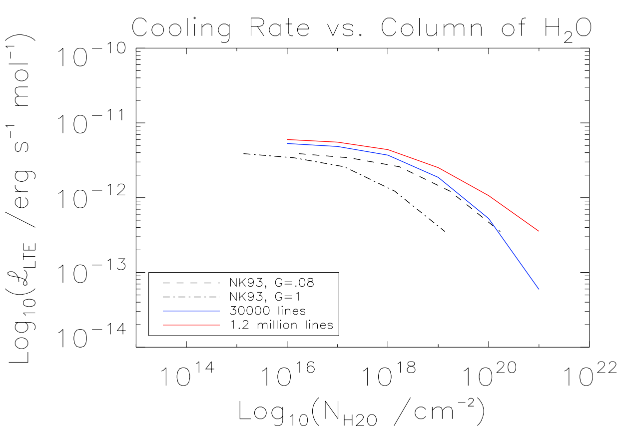
The melting of chondrules in the solar nebula, a long-standing problem in the field of meteoritics, appears close to being solved. Melting of chondrules by 1-D nebular shocks has been modeled by several authors, including Iida et al. (2001; INSN [1]), Desch & Connolly (2002; DC02 [2]), and Ciesla & Hood (2002; CH02 [3]). Although these models are based on slightly differing assumptions, they predict similar thermal histories for chondrules, with cooling rates in the range $10^2 - 10^3\,\mathrm{K\,hr^{-1}}$, consistent with the timescales for crystallization inferred from furnace experiments [4]. As reviewed by Desch et al. (2005 [5]), melting of chondrules by nebular shocks is also consistent with a host of other derived constraints on chondrule formation, including formation in the presence of chemically complementary matrix dust, formation in a high-pressure environment, the frequency of compound chondrules and their correlation with chondrule cooling rate.

While the various shock models [1-3] are similar, they make fundamentally different assumptions about the flow of radiation (see [5]). One key difference is the ultimate post-shock gas temperature, which feeds back to the radiation field as a boundary condition. Both INSN and CH02 assume that radiation escapes the system effectively, returning the post-shock gas to the ambient temperature. This is formally inconsistent with the 1-D approximation, because in 1-D there is nowhere for the radiation to escape *to*; instead radiation must propagate into the post-shock gas (as a stationary Marshak wave; see [6]) and heat it. Post-shock gas returns to the ambient temperature in a time t only if t exceeds the radiation diffusion timescale $t_{\mathrm{rd}} = 3L^2\rho^2 c_v \kappa/(16\sigma T^3)$. Here L is the lateral extent of the shocked region, ρ is the gas density, c_v its specific heat apacity, T its temperature, σ the Stefan-Boltzmann constant, and κ the Rosseland mean opacity (see [6], page 552). Assuming $\rho = 6\times10^{-9}\,\mathrm{g\,cm^{-3}}$ and $\kappa = 5\,\mathrm{cm^2\,g^{-1}}$ [7], the mean free path of thermal photons is $(\rho\kappa)^{-1} \approx 330$ km and $t_{\mathrm{rd}} > 170$ hours if $L > 10^5$ km. Radiation emitted by gas within 170 hours or $V t_{\mathrm{rd}} \sim 6\times10^5$ km of the shock front has nowhere to escape to, and for shocks of this size it is inappropriate to violate the 1-D approximation and let the post-shock gas return to the ambient temperature, as was done by [1] and [3]. (DC02 did not violate the 1-D assumption but unfortunately used an incorrect jump condition from [8], thereby overestimating the radiation field.) A second key difference is how the models treated line cooling, emission of photons from rotational and vibrational transitions of CO and H_2O molecules. DC02 and CH02 assumed the post-shock region was too optically thick to such photons for any to escape and cool the gas, while INSN assumed the post-shock region was so optically thin that all such photons escaped easily, greatly cooling the gas. While cooling rates of gas and chondrules in the DC02 and CH02 models are set by how fast they can move several optical depths from the shock front ($\sim 4\times(1\,\mathrm{km\,s^{-1}})/(330\,\mathrm{km}) \sim 10^2\,\mathrm{K\,hr^{-1}}$), cooling in the INSN models is dominated by line cooling and is $> 10^3\,\mathrm{K\,hr^{-1}}$. These cooling rates are similar and neither is inconsistent with chondrule cooling rates [4], but they are distinct.

Is the post-shock gas effectively optically thick or thin to line photons? To answer this question, we start by using the cooling rates of NK93 [9] employed by INSN. Protoplanetary disk gas is dense enough that molecular energy levels are populated in thermodynamic equilibrium, and the emission rate per volume is $n_{\mathrm{H2O}}\mathcal{L}_{\mathrm{LTE}}$, where $\mathcal{L}_{\mathrm{LTE}}$ is a function of $\tilde{N}$, an effective optical depth between the location of cooling post-shock gas and the shock front. The geometry of NK93 most approriate to cooling of post-shock gas is the case of cooling from the center of a static plane-parallel slab, so $\tilde{N} = n_{\mathrm{H2O}} d/\Delta v$, where $d = 2z$ (z is the distance of gas from the shock front), and Δv is the thermal velocity of *water molecules*. In addition, one must reduce the cooling rate by a factor of 2 because line emission into the post-shock gas does not cool it. The energy density of gas is $e = 2.8\,n_{\mathrm{H2}}kT$, and $\mathrm{d}e/\mathrm{dt} = V\mathrm{d}e/\mathrm{dz} = -n_{\mathrm{H2O}}\mathcal{L}_{\mathrm{LTE}}(\tilde{N})/2$, so we derive the following: $\mathrm{d}T/\mathrm{d}\tilde{N} = -(m_{\mathrm{H}}\Delta v/4k\rho V)\mathcal{L}_{\mathrm{LTE}}(\tilde{N})$. For a given type of line photon this can be integrated as a function of $\tilde{N}$ to find the maximum total temperature drop far into the post-shock region due to that type of line emission. Vibrational photons from H_2O are most effective at cooling the post-shock gas, but even for these photons high optical depths $\tilde{N} \approx 10^{20}\,\mathrm{cm^{-2}\,km^{-1}\,s}$ are reached after only 640 s (assuming pre-shock $\rho = 10^{-9}\,\mathrm{g\,cm^{-3}}$ and $V_{\mathrm{s}} =$

$7\,\mathrm{km\,s^{-1}}$, and a water-to-gas ratio $n_{\mathrm{H2O}}/n_{\mathrm{H2}} = 8 \times 10^{-4}$, and a post-shock temperature 2000 K). Within those 11 minutes gas can cool by 290 K by H_2O vibrational photons. In contrast, vibrational photons from CO cool the gas by < 20 K, and rotational photons from H_2O and CO become optically thick so rapidly they lead to a temperature drop of only a few K in the same time. We find that the post-shock gas is effectively optically thick to the line photons considered by INSN (CO rotational and vibrational and H_2O rotational), but perhaps not H_2O vibrational photons.

To better quantify the cooling from H_2O line photons, we have calculated the rate at which photons are emitted by warm H_2O gas using the HITRAN database of lines [10]. We have assumed thermal population of levels, as in the limit considered by NK93, but we have used exact escape probabilities [11], and we have used all 1.2 million lines of the HITRAN database instead of the 300,000 lines available to NK93. Our cooling rate as a function of column density into the post-shock region is shown in Figure 1, with the results of NK93 shown for comparison. The results are quite comparable, although we find that the gas does not become optically thick quite as fast as NK93 found it to. We attribute the difference to the extra 0.9 million lines we used, all of which are between high, sparsely populated states and therefore optically thin; these continue to cool the gas somewhat farther into the post-shock region. We therefore find that vibrational lines of H_2O are somewhat more effective at cooling the post-shock gas than the rates from NK93 would imply and will lead to significant drops in temperature.



The final drop in temperature will depend on the dynamics of gas in the post-shock region but we estimate the drop here using the temperature-dependent rates from NK93. The cooling rate is very sensitive to temperature, dropping by a factor of 20 between $T = 2000$ K and $T = 1000$ K [9]. At lower temperatures, H_2O molecules are not collisionally excited as often (and so don't emit photons), and the photons that are emitted are all among the low-lying, highly populated levels with optically thick transitions. Line cooling is very effective at $T \approx 2000$ K, leading to cooling rates $\sim 10^3\,\mathrm{K\,hr^{-1}}$ and rapid temperature drops of several hundred K, but by the time the gas has cooled to 1600 K, the cooling rates drop below $10^2\,\mathrm{K\,hr^{-1}}$, and decrease further at lower temperatures. Cooling by emission of vibrational photons from H_2O brings the gas temperature down from above 2000 K to a temperature on the order of 1500 K much faster than the optically thick models of DC02 and CH02 find. In the chondrule crystallization temperature range, 1400 - 1700 K [4], vibrational lines of H_2O impose a lower limit on the cooling rate of gas and chondrules of $\sim 10^2\,\mathrm{K\,hr^{-1}}$ (comparable to the cooling rates found by CH02 and DC02). The combined effect is that H_2O vibrational line photons seem to effectively "thermostat" post-shock gas at the chondrule crystallization temperatures and impose a universal cooling rate to most chondrules. Calculations are underway to incorporate line cooling into a full shock code and compute new thermal histories of chondrules.

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