Keeping chondrules hot
B.C. Johnson¹, H. J. Melosh¹,², L. Grossman³, F. J. Ciesla³

Abstract:
• Chondrules are the mm-sized previously molten droplets that give chondritic meteorites their name.
• Meteorite researchers have been impressed by the similarities between impact-generated melt droplets [1,2] and chondrules [3].
• The significant degree of sodium retention that chondrules exhibit implies that chondrules were generated in high-pressure, dust-rich environments, possibly by planetesimal impacts [4].
• The igneous textures of chondrules indicate that chondrules were initially flash-heated above the liquidus and then cooled at a rate of 10-1000 K/hr [5].
• Our order of magnitude estimates suggest that impacts between planetesimals that are ~1-100 km in diameter can produce plumes with cooling rates of 10-1000 K/hr, consistent with the estimated cooling rates of chondrules.
• This is consistent with the 1-10 km diameter impactors required to make mm-scale melt droplets [2].

Results:

Figure 1: A cartoon illustrating the basic problem we are trying to model. A planetesimal impact creates a spray or plume of melt droplets that expands into free space. The melt droplets cool as the plume expands and thermal radiation escapes to free space.

Figure 2: Temperature as a function of position in the plume. The different line styles and colors represent different times after expansion and cooling began, as indicated by the legend. This plume has a mass corresponding to an 18 km diameter planetesimal and a constant chondrule diameter of 1 mm.

Figure 3: Cooling rate plotted as a function of temperature, for the same plume shown in Figure 2. The different line colors and styles represent different cells within the plume. The normalized positions of these cells are indicated in the legend. The bold black line is the mass averaged cooling rate, which has a maximum value of 150 K/hr. The thin black dotted-dashed at 1400 K represents the solidus, an approximation to the temperature where crystallization ends [5].

Figure 4: The maximum mass averaged cooling rate is plotted as a function of equivalent impactor diameter. The equivalent impactor diameter is the size of an impactor that will have a mass equal to the mass of the plume. The different colored lines represent different chondrule sizes as indicated by the legend. Each ‘+’ mark represents a different model run.

Modeling details:
We use a heat capacity of 1000 J/kg/K typical for rock and a density of liquid silica, 2500 kg/m³. The melt droplets are assumed to be black bodies and thus have a collective opacity of κ=3ϕ/(4r), where ϕ is the fraction of the volume occupied by the droplets and r is the radius of the of the melt droplets. For simplicity we neglect the opacity of any vapor that may be present, i.e. impact-produced vapor or gas in the solar nebula.

Figure 5: A schematic of the model plume showing the initial conditions. At Rmin there is a reflecting boundary condition and the velocity is set at zero. For the plume shown in Figure 2 and 3, Rmin= 10 km. The velocity increases linearly with distance up to a maximum value of 1 km/s at a distance Rmax= 10 Rmin. To avoid material reaching temperatures of 0 K and to simulate local thermal equilibrium at ~1 AU, the edge of the plume has a constant temperature boundary condition of T=300 K.

Figure 6: Mass in cell plotted against normalized position and velocity. Each mark represents one cell. We initialize the mass by requiring the plume to be 50% void at Rmin. The mass then decreases as M oc R². We make this choice, rather than the expected power law dependence on velocity, so that the plume has significant mass at higher velocities.

References: