Keeping chondrules hot

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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].

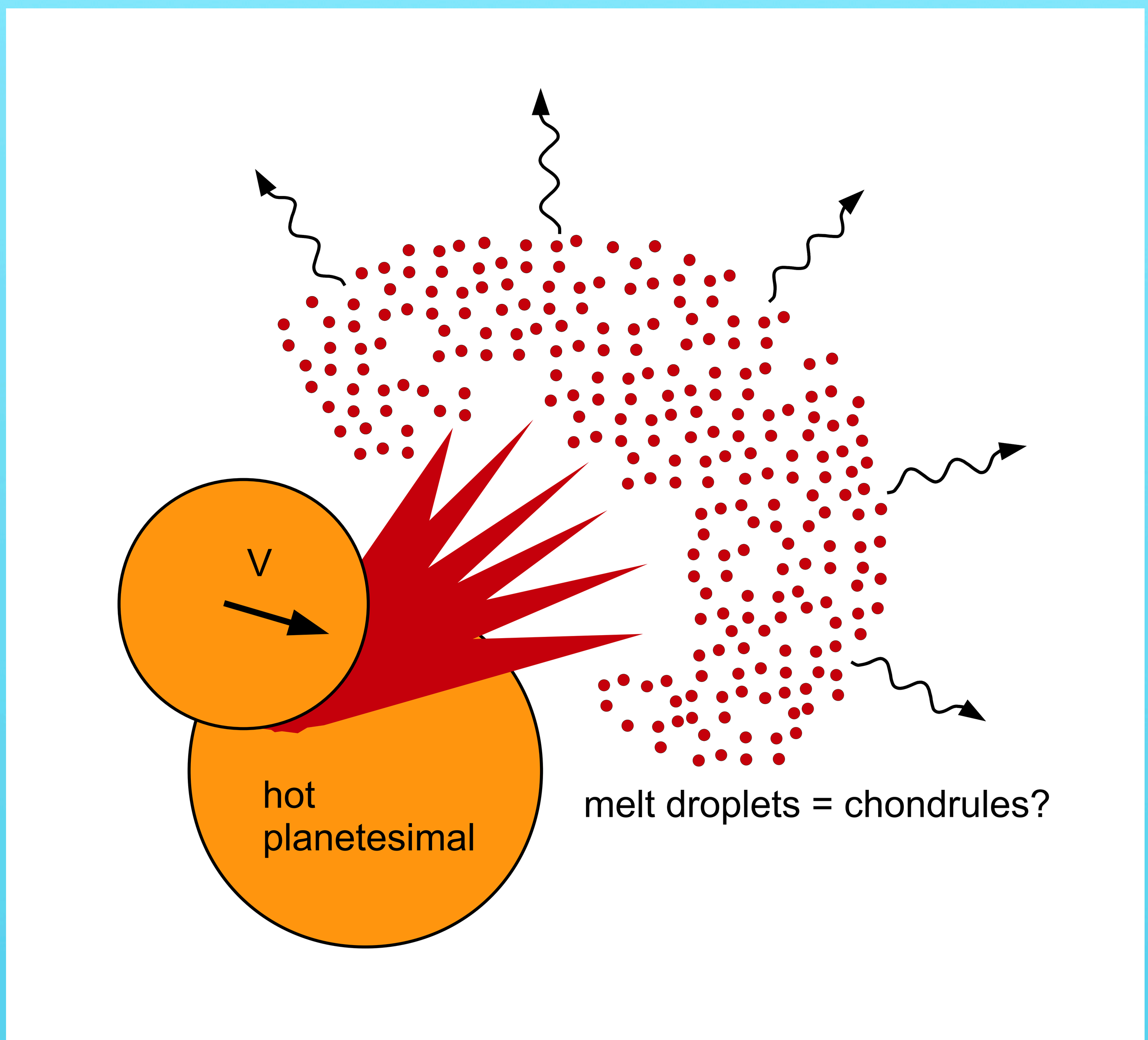

Figure 1: A cartoon illustrating the basic problem we are trying to model. A planetesimal impact creates a spray or plume of melt droplets that expands into free space. The melt droplets cool as the plume expands and thermal radiation escapes to free space.

Modeling:

To estimate the cooling rates of impact-produced melt droplets, we model the ejected material as a spherical plume with the outer edge of the plume expanding into free space at a velocity of 1 km/s. In our model we assume all of the melt droplets are of equal size and start with an initial temperature of 2000 K. We determine the cooling rates using a 1-D radiative transfer code, which uses the diffusion approximation. We benchmarked this code using the non-equilibrium Marshak diffusion problem [6]. Our model assumes that the mass, ejected at any velocity, is distributed evenly over one of 400 initially equally spaced spherical shells called cells. This assumption will tend to underestimate the opacity of the material and leads to an overestimate in the cooling rate for the outer portions of the plume.

Results:

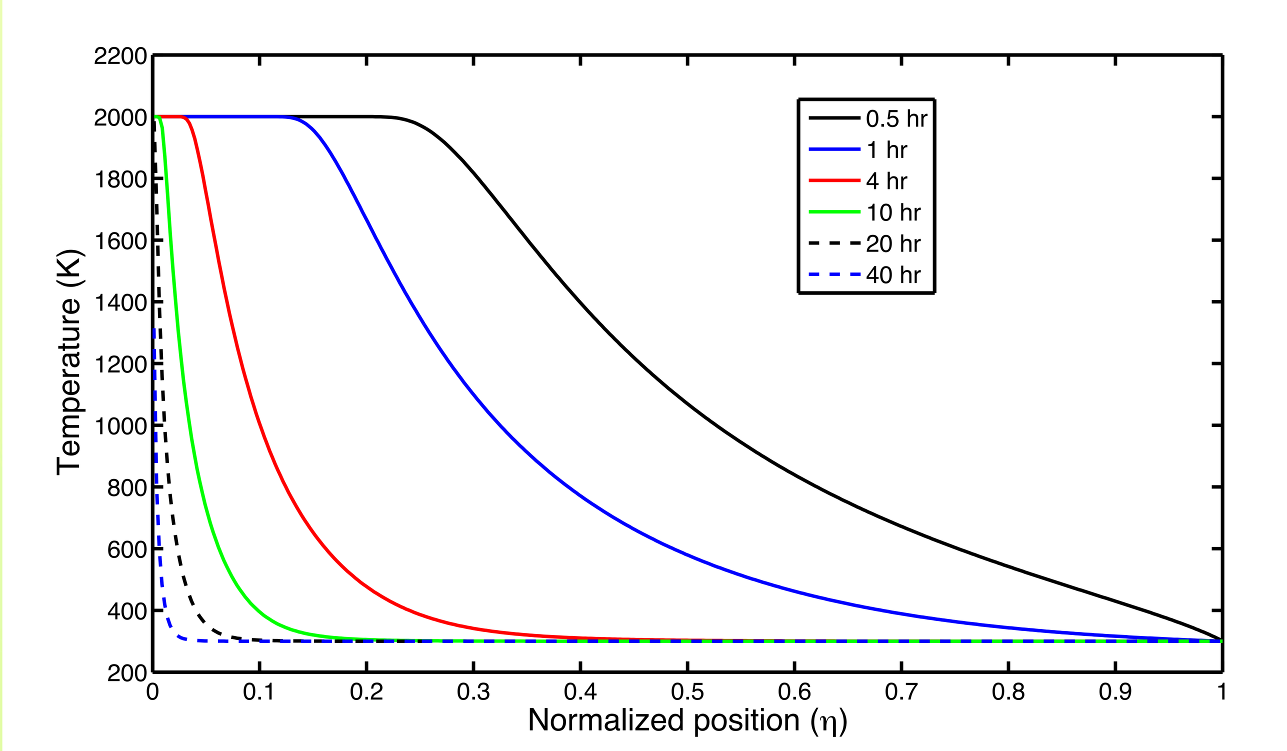

Figure 2: Temperature as a function of position in the plume. The different line styles and colors represent different times after expansion and cooling began, as indicated by the legend. This plume has a mass corresponding to an 18 km diameter planetesimal and a constant chondrule diameter of 1mm.

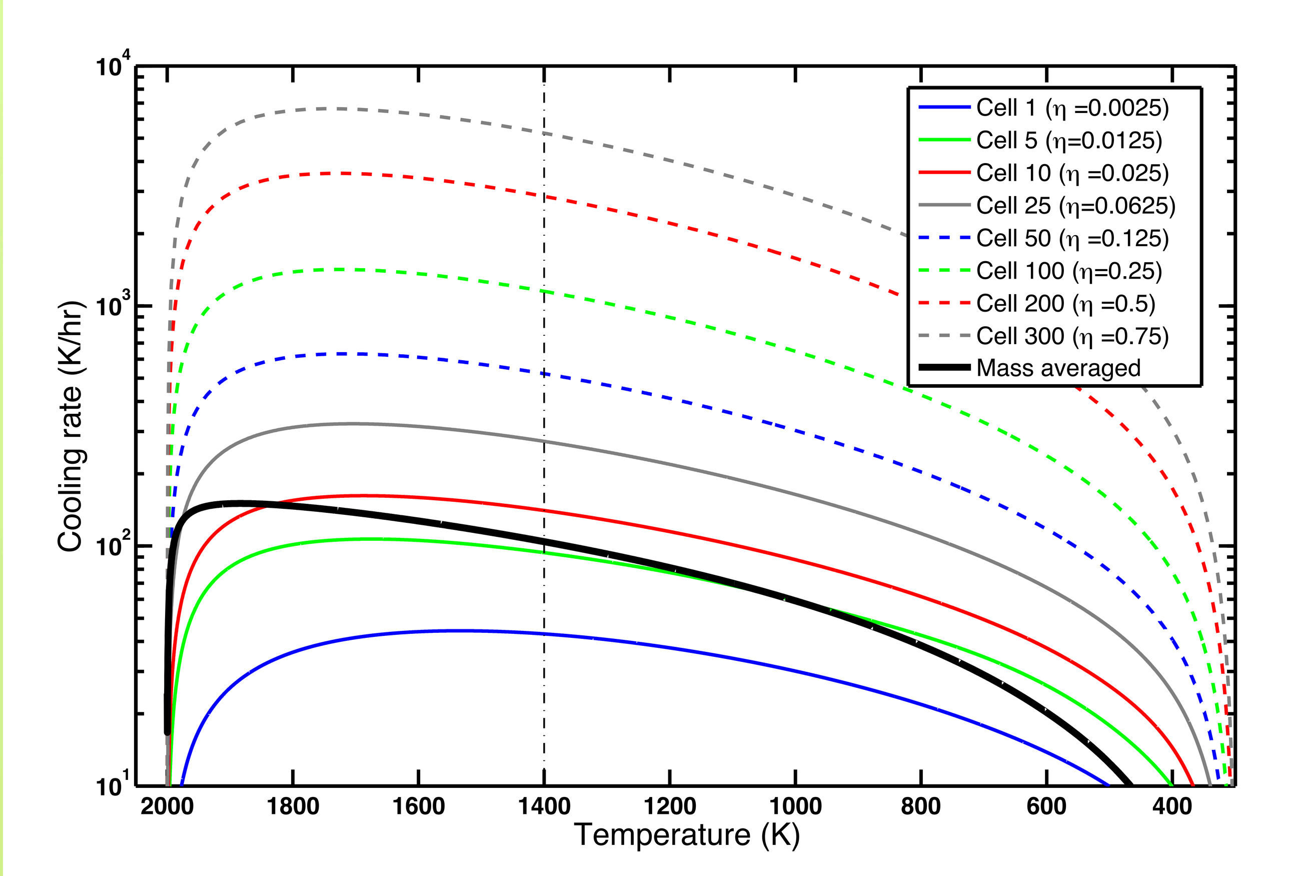

Figure 3: Cooling rate plotted as a function of temperature, for the same plume shown in **Figure 2**. The different line colors and styles represent different cells within the plume. The normalized positions of these cells are indicated in the legend. The bold black line is the mass averaged cooling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

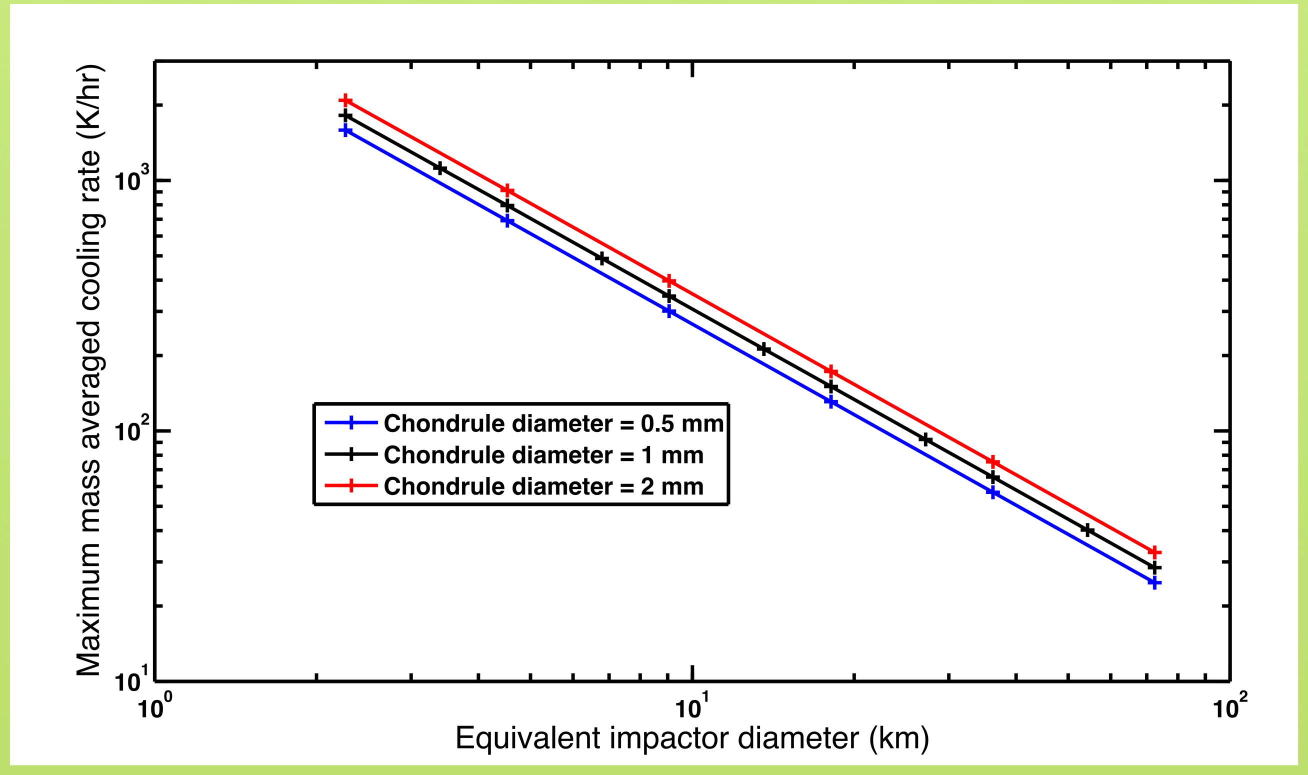

Figure 4: The maximum mass averaged cooling rate is plotted as a function of equivalent impactor diameter. The equivalent impactor diameter is the size of an impactor that will have a mass equal to the mass of the plume. The different colored lines represent different chondrule sizes as indicated by 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/m^3. The melt droplets are assumed to be black bodies and thus have a collective opacity of $\kappa=3\phi/(4r)$, 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.

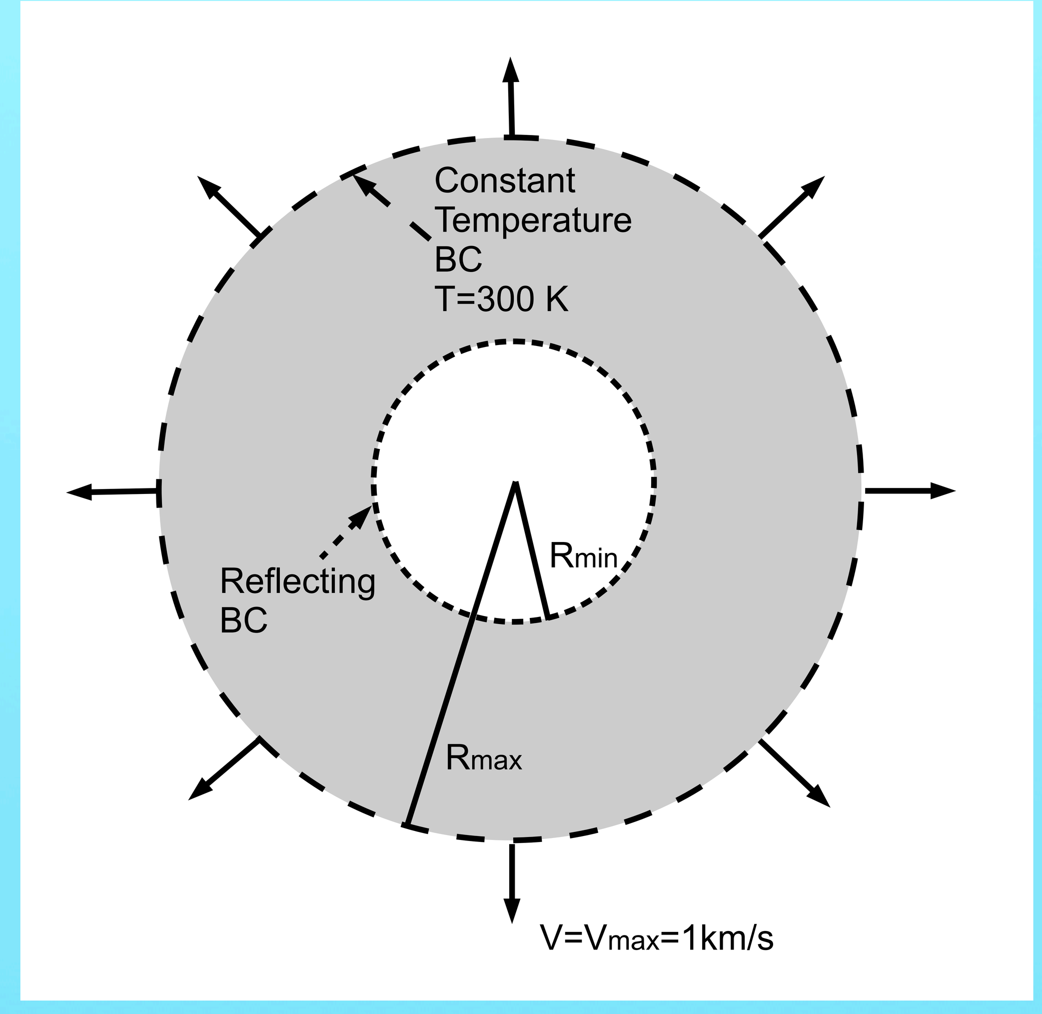

Figure 5: A schematic of the model plume showing the initial conditions. At R_{min} there is a reflecting boundary condition and the velocity is set at zero. For the plume shown in **Figure 2** and **3,** R_{min}= 10 km. The velocity increases linearly with distance up to a maximum value of 1 km/s at a distance R_{max}= 10 R_{min}. 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.

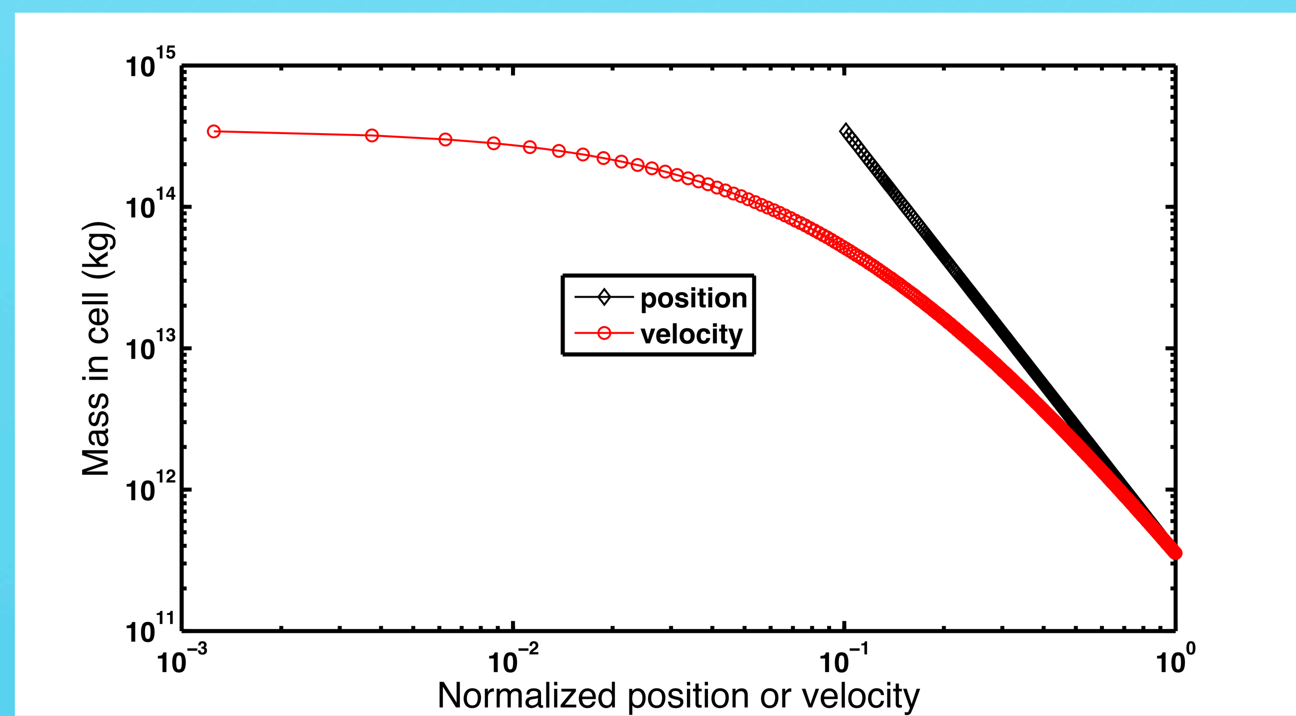

Figure 6: Mass in cell plotted against normalized position and velocity. Each mark represents one cell. We initialize the mass by requiring the plume to be 50% void at R_{min}. The mass then decreases as $M \propto R^{-3}$. We make this choice, rather than the expected power law dependence on velocity, so that the plume has significant mass at higher velocities.

References:
[1] Simonson, B.M. and Glass, B.P. (2004). Annu. Rev. Earth Planet. Sci. 32, 329–361. [2] Johnson, B.C. and Melosh, H.J. submitted to Icarus. [3]Asphaug, E. et al. (2011) Earth Planet. Sci. Lett. 308, 369-379 [4] Fedkin, A.V. and Grossman, L. (2013). Geochim. Cosmochim. Acta 112, 226–250. [5] Desch, S.J. et al. (2012) Meteorit. Planet. Sci. 47, 1139-1156. [6] Su, B. and Olson, G.L. (1996) J. Quant. Spectrosc. Radiat. Transfer 56, 337-351.