

**COOLING RATE DISTRIBUTIONS IN EJECTA PLUMES.** M. L. A Richardson<sup>1</sup>, N. Ouellette<sup>2</sup>, M. Metcalf<sup>2</sup> and M. Morris<sup>2,3</sup>, <sup>1</sup>Department of Physics, University of Oxford: (Mark.Richardson@physics.ox.ac.uk). <sup>2</sup>Physics Department, SUNY Cortland. <sup>3</sup>School of Earth and Space Exploration, Arizona State University.

**Introduction:** During the hierarchical assembly of planetary bodies in our protoplanetary disk, collisions between planetesimals were common. These collisions resulted in a significant amount of material ejected into the surrounding nebula. Astronomical observations are now able to reveal some of the protoplanetary disk dynamics that occur [1]. However, such collisions are currently unresolvable. Instead, meteoritic data that probe such events could prove crucial for understanding the nature of the colliding bodies and the surrounding nebula.

Based on their ages and negligible inter-chondrule matrix, non-porphyritic CH/CB chondrules (mostly skeletal and cryptocrystalline in texture) are thought to derive from a vapor-melt ejecta plume resulting from such planetesimal collisions [2][3][4]. Additionally their texture suggests cooling rates in excess of 2000 K/hr [5]. In this work we explore the dynamics and cooling rates in an ejecta plume, illustrating their broad consistency with the observed cooling rates in CH/CB chondrules.

**Numerical Methods:** We begin with the model from [6], a smoothed particle hydrodynamics (SPH) simulation of a 30 km radius basaltic projectile colliding with a 100 km radius basaltic target planetesimal. This results in most of the projectile and some target material forming an ejecta plume. In their simulations, the ejected material has its pressure set to zero and evolves ballistically, allowing the model to adiabatically expand, consistent with a pressure-bound vapor phase with sub-resolution sized melt droplets.

Using the method in [7], we map the dataset 4000 s after collision into the adaptive mesh refinement (AMR) code FLASH [8]. We choose this AMR code for the ability to: i) model the nebular medium as it impacts the dynamics of the plume and will be shock-heated as the plume expands; ii) implement a radiative transfer model so droplets in the plume may radiate and cool, accounting for the opacity in the plume and nebula; iii) fix the spatial resolution as the plume expands.

However, the choice in SPH to set the ejecta pressure to zero leads to subsequent difficulties when mapping to AMR. The goal was to allow for ballistic evolution, essentially shutting off hydrodynamics. In our model, we include the interaction between the nebula and the plume, and also allow the plume to evolve under self-gravity. Thus we set the initial pressure in our model (both in the mapped material and in the ambient

nebula) to a constant value, consistent with the pressure in the plume if it was mostly a pure ideal-gas vapor. Thus, initially the plume is pressure-bound, but as it expands it shock-heats the nebula, and any collapse or expansion has a resulting change in pressure.

To estimate temperature, we assume a uniform initial temperature of  $T_o = 2200$  K. The plume cools adiabatically as it expands. We found the most effective method to model the cooling was to include a mass scalar that advects with the flow. At present, this neglects heating from shocks. We initialize this mass scalar to the inverse of the local density, such that at later times the value of the mass scalar in a cell is a mass-weighted average of the initial density of all gas that has merged into this cell. Neglecting the melt, and assuming the vapor is an ideal gas, we have:

$$T(\mathbf{x}, t) = T_o [\rho(\mathbf{x}, t) / \rho_o(\mathbf{x}, t)]^{\gamma-1} = T_o [\rho(\mathbf{x}, t) X(\mathbf{x}, t)]^{\gamma-1},$$

where the temperature,  $T$ , is found at every point in space,  $\mathbf{x}$ , and time,  $t$ , as a function of the initial temperature, the ratio of the specific heats,  $\gamma = 1.4$ , the local density,  $\rho$ , and the mass scalar,  $X$ , which is the inverse of the initial density,  $\rho_o$ . We assume the plume is a vapor-melt mix, where sub-mm droplets of mean density  $2.7 \text{ g/cm}^3$  are in thermal equilibrium with the lower density vapor.

To measure the cooling rates in the bulk vapor requires introducing tracer particles that move with the plume. With these particles, we can sample the temperature of regions of the plume as it moves, giving a comoving thermal history. Tracer particles are initialised randomly, following a probability distribution given by the mass fraction in a cell. Unfortunately, unlike SPH, which is a pure Lagrangian method, tracer particles implemented in an Eulerian code will not stay perfectly within the same parcel of gas. We attempt to account for times when the tracer particle slips out of its parcel by discounting a timestep if it has a very rapid change in temperature that is not maintained in subsequent timesteps. We calculate cooling rates from the change in temperature over the remaining time step.

In our models with radiative transfer, we keep the vapor pressure constant and only include changes in the temperature of the melt due to radiative cooling. This maintains a near constant pressure, limiting errors in our near ballistic model of the plume dynamics.

**Results and Discussion:** We present results from a 2 km resolution Non-RT simulation with 835 tracer

particles at mapping, which output their temperature at each step. In Figure 1 we plot the density of the plume and overplot several tracer particles that have a range of cooling rates. The plume has a mass of  $1.23 \times 10^{20}$  g. We can use projections to identify trends between a particle's original location in the plume and its cooling rate. We find that regions near the edge of the plume cool the fastest, with average cooling rates of 2500-6500 K/hr through 1400-1600 K. These rates are converged when we compare with a higher resolution run.

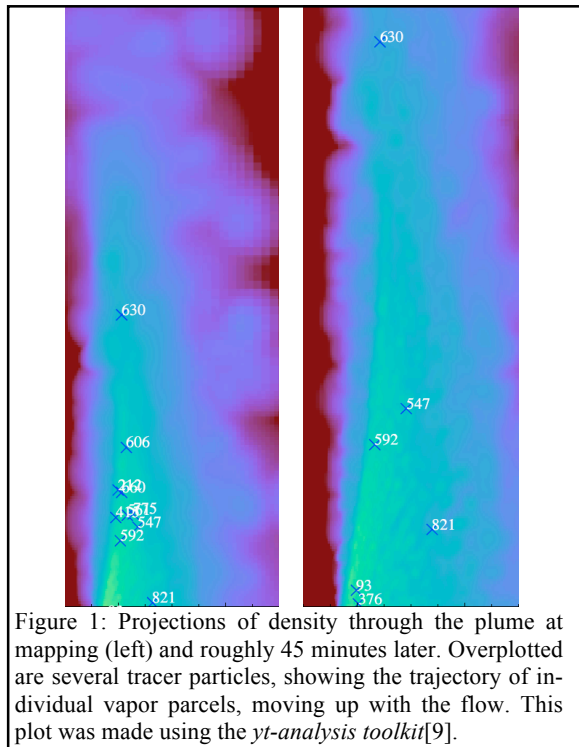


Figure 1: Projections of density through the plume at mapping (left) and roughly 45 minutes later. Overplotted are several tracer particles, showing the trajectory of individual vapor parcels, moving up with the flow. This plot was made using the *yt-analysis toolkit*[9].

A single fluid parcel will cool at different rates throughout its evolution. We have characterized two different cooling rates for each tracer particle. We define the 75th percentile cooling rate as  $\dot{T}_{75}$ . We define as  $\dot{T}_{1400-1600}$  the average cooling rate of the fluid while between 1400-1600 K (the crystallization temperature range). In Figure 2 we plot the number fraction of tracers as a function of initial density and cooling rate. For  $\dot{T}_{1400-1600}$  ( $\dot{T}_{75}$ ) we find 19% and 2.5% (57% and 19%) of the plume by mass has cooling rates of 1000-2000 K/hr, and  $> 2000$  K/hr, respectively. In both plots we see that the cooling rate is lower in the most dense gas, but then flattens at lower temperatures. While the upper quartile of cooling rates asymptotes slightly above 2000 K/hr, the average cooling asymptotes at roughly 1000 K/hr at cooler temperatures. Thus in general cooling rates are seen to decrease with decreasing temperature. Finally, the fluid that cools most efficiently is found with initial densities of  $\sim 3 \times 10^{-3}$  g/cm<sup>3</sup>. Thus we predict a broad range of cooling rates, for which some

are consistent with the inferred rates for CH/CB chondrules. With a full radiative transfer model we would expect all cooling rates to be even more rapid.

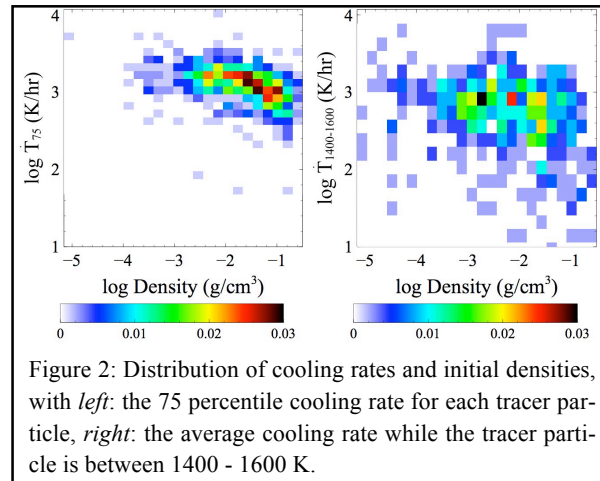


Figure 2: Distribution of cooling rates and initial densities, with *left*: the 75 percentile cooling rate for each tracer particle, *right*: the average cooling rate while the tracer particle is between 1400 - 1600 K.

**Conclusions:** We present three dimensional AMR simulations of an ejecta fan, using tracer particles to probe the comoving cooling rate of individual fluid parcels. We find a variety of cooling rates, with the most rapid ones above 2500 K/hr occurring at the periphery of the plume, at intermediate densities. The most dense regions of the plume have characteristically lower cooling rates, with  $\dot{T}_{75}$  of roughly 800 K/hr and  $\dot{T}_{1400-1600}$  of 100 K/hr. At lower initial densities the plume is more efficient at cooling, with 19% by mass cooling at a rate of 1000-2000 K/hr. The rapid cooling rates are consistent with CH/CB chondrules. Other cooling rates are predictive of the range of rates we could observe in the meteoritic record.

The cooling rates presented here assume a coupling between the melt and vapor phases. This work is improved by including a droplet model and radiative transfer. We will discuss our progress incorporating these two additional physical processes into our simulations.

**References:** [1] Andrews S. M. (2016) *ApJ*, 820, L40-44. [2] Rubin A. E. et al. (2003) *Geochim. Cosmochim. Acta* 67, 3283-3298. [3] Campbell A. J. and Humayun M. (2004) *Geochim. et Cosmochim. Acta* 68, 3409-3422. [4] Krot A. et al. (2005) *Nature* 436, 989-992. [5] Hewins R. H. et al. 2005, *ASP Conference Series*, 341, 286-316. [6] Asphaug E. et al. (2011) *EPSL* 308, 369-379 [7] Richardson M. L. A. et al. (2009) *ApJ* 771, 81-93. [8] Fryxell B. et al. (2000) *ApJS* 131, 273-334. [9] Turk M. et al. (2011) *ApJS* 192, 9-24.